1995

Effect of agricultural fiber reinforcement on the mechanical properties of a recycled polyethylene plastic composite material

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EFFECT OF AGRICULTURAL FIBER

REINFORCEMENT ON THE

MECHANICAL PROPERTIES OF A RECYCLED

POLYETHYLENE PLASTIC COMPOSITE MATERIAL

A Dissertation

Submitted

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Industrial Technology

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May 1995

UMI Number: 9536141

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ABSTRACT

This study determined the effect of certain agricultural fiber reinforcements on the tensile and impact mechanical properties of a recycled polyethylene plastic composite material. The purpose of the study was to provide information on certain mechanical properties of a recycled polyethylene plastic material as part of a coordinated materials application process.

A prototype product run of the plastic composite material was done and test specimens were selected from this material. Notch impact, tensile, and flexure tests were conducted on test specimens. Test procedures complied with accepted standards from The American Society For Testing and Materials (ASTM). Tests were conducted on 193 notch impact specimens, 106 tensile test samples, and 13 flexure test specimens.

Data collected during these tests were statistically analyzed by standard Analysis of Variance (ANOVA) tests at the 0.05 level of significance. Standard statistical procedures were applied to the data to ascertain if unexpected manufacturing or process variables were encountered. The effects of individual and combined treatments effects were analyzed for significance in regard to the influence these factors had on notch impact, tensile, and flexural strength. A statistically

significant ($p = 0.05$) mean value difference was determined to exist between the effect of different lengths of reinforcement fiber, different volume fraction percentages of fiber reinforcement material, different test temperatures, and different types of fiber reinforcement material. Mean experimental values for each treatment effect were generated. Data were organized in appropriate data tables and graphical presentations.

DEDICATED TO

MY PARENTS

DALE and MARCIA COURBAT

ACKNOWLEDGEMENTS

No one who arrives at this stage of their career can be said to have traveled this path by himself. We all follow in the footsteps and with the people who have been in our lives. Knowing that, I would like to express my appreciation to the following people.

Most importantly to my family who have supported and encouraged me every step of this journey. I wouldn't have made it here without your assistance.

To my committee, Drs. Ahmed Elsawy, Bart Bergquist, Scott Helzer and William Callahan for their guidance, criticism and encouragement and especially to the BOSS (Dr. Mohammed Fahmy) for being more than a teacher but also a friend, mentor and role model.

A special thanks must go to people at Hammer's Plastics Recycling Corporation, Brian Harper and Don Lawler, for their generous support. And last, but not least, to my friends and colleagues at the University of Northern Iowa.

I have had the good fortune and pleasure of being the friend and wingman of Dave Bradney throughout most of graduate school. Our friendship and cooperation has made this experience one of the most meaningful and interesting in my life.

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CHAPTER 1

INTRODUCTION

History records that mankind has always been experimenting with and changing the components found in nature, rearranging them in civilization's ongoing search for improved ways to accomplish things. The record of this process is as long and varied as any in recorded history. At least one reference work on the history of technology defines its subject as, "how things are commonly done or made" (Kranzberg & Pursell, 1967, p. 5). A narrower definition of technology, according to Kranzberg and Pursell (1967) is that:

> In its simplest terms, technology is man's efforts to cope with his physical environment both that provided by nature and that created by man's own technological deeds, such as cities and his attempt to subdue or control that environment by means of his imagination and ingenuity in the use of available resources. (p. 4)

Forbes (1967) contends that the successful mastery and application of this type of technology was crucial to the development of early civilizations. The beginnings of agriculture, the development of early permanent settlements, the establishment of extensive trade routes and the invention of novel forms of transportation were all directly related to and dependent upon a better understanding of natural materials.

Early historical records indicate that this process of manipulating materials was plagued by many mistaken concepts and inaccurate information. According to Gunn (1979), early attempts at materials engineering, were called alchemy, and began around 410 A.D. with a search for the Elixir of Life and the Philosopher's Stone. A more practical application of materials engineering, common to many societies, dealt with improving basic building materials. Adding plant fiber to clay was, according to Gordon (1976), a common method of controlling the cracking of clay bricks and pottery when they were dried prior to being used. This simple step of adding a second material to the clay to improve performance characteristics, is according to English (1990), a fundamental advancement when compared to previous material usage. From this modest beginning, the sciences of metallurgy, materials science and materials engineering have evolved into a multidisciplinary field concerned with the generation and application of knowledge relating to the composition, structure, and processing of materials to their properties and uses (Parker, 1993, p. 685; Smith, 1993, p. 4-5).

The inventions, innovations, and applications of this new multidisciplinary field have had profound and unexpected consequences for society. Unique examples of unconventional matrix and reinforcement materials applications have ranged from the deadly to the ridiculous. Famous weapons like

Japanese samurai swords, Damascus gun barrels and the Mongol cavalry bow of the Mongol warrior were all made of composite materials (Strong, 1989, p. 1). As recently as World War II, Allied governments gave serious consideration to the concept of manufacturing composite icebergs for use as disposable mid-Atlantic airfields.

Other results of this technological process have had a more profound and longer lasting impact on society. According to Hall (1967), the innovation of cannon manufacturing in the 15th century resulted in a dramatic increase in the need for fuel supplies. As a consequence, a shortage of wood resulted. This forced the change to coal, as an alternative fuel source. Such a shift resulted in a need for coal that forced millions of men into a dangerous and arduous livelihood in the mines, while it blighted industrial civilization with its own blackness (p. 83).

Such wide ranging impacts and consequences have repeated occurred as mankind has developed technological expertise. Kranzberg and Pursell (1967) state that much of past abounds with failures--schemes that went awry, machines that wouldn't work, processes that proved inapplicable--yet these failures form an important part of the story of man's attempts to control his environment (p. 5). Recent experiences have indicated that mankind has not yet acquired any better expertise in planning or controlling the impact of technological advancements. Improved sensory and informational networks catalog a growing list of environmental problems directly linked to human activities. Problems such as the destruction of the ozone layer, the effect of greenhouse gases on the global environment, acid rain, decreasing biological diversity, deforestation, desertification, and hazardous waste management are becoming issues which cannot be ignored by technologists and engineers.

According to Drachmann (1967), engineering goes beyond machines and processes. One of the major engineering tasks is to manage effectively the resources by a better understanding of the limitations and the potential of tools and materials (p. 65). The emphasis on the importance of the properties and behavior of materials being used, in different applications, is crucial to society. This is because that what we achieve technically has always been limited by the properties of the materials of construction (Gordon, 1976, p. 16). Developing alternative materials which alleviate consumer pressure on limited traditional construction materials and recycle consumer waste are of significant importance to society.

The world, according to Robert J. Eaton (1986), Vice President and Group Executive, Technical Staffs Group, General Motors Corporation, is in the midst of a Second Industrial Revolution. Eaton states that many technologies are expanding exponentially and the impact of this Second

Industrial Revolution is dwarfing the first Industrial Revolution. One area of technological advancement that will be critical in this new revolution is the area of materials science (p. 41).

Nowhere are the issues involved in this process more dramatically illustrated than in the debate over the utilization of timber crops and the changing expectations and demands on American forests. The management practices and policies of federal, state, industrial, and private nonindustrial forests are being questioned and challenged as never before. Issues such as biodiversity, spotted owls and the old growth forests, clear cutting, below cost sales, recreational use, pollution, jobs, and a swelling suburbia are combining to spark heated debates over just what should be done in America's forests (Hubbard, 1989; Shands, 1989; Walt, 1989; Wolfe & Mobley, 1989).

Timber is the focus of this debate because it is the nation's most valuable agricultural resource valued at sales of $200 billion per year and accounting for 24% of the total agricultural harvest and because it has become a focal point of ecological damage (Walt, 1989, p. 27). Controversial management practices, dramatic urbanization of the nations wildlands and changing societal values are challenging and, in some cases, stopping traditional forestry practices. With increased demand for forestry products, both domestically and for export, American policies and priorities in regard to forestry utilization are now in a state of flux.

Consumer demand and pressure on this agricultural resource is, like all agricultural products, greatly influenced by global conditions. The state of the world's forests, according to Walsh (1989), is varied and greatly dependent on region. Total global losses to deforestation have reached 247 million acres during the last decade with dramatic changes in Africa, India, and South America. The impact of forestry losses of this magnitude, upon the regional and global ecology, can only be estimated but the changes that are forecast are troubling. The demand for valuable resources and the impact of the population increases in the Third World are also contributing to the unprecedented alteration of the global ecosystem. Increased needs for fuel, commercial logging, and especially slash and burn agricultural practices are destroying forests, primarily tropical forests, at the rate of 50 acres a minute (Golob & Brus, 1990; Myers, 1991). The impact of these activities has been, according to Houghton and Woodwell (1989), to begin an uncontrollable change in the global climate. American forests and forestry products are inevitably drawn into this controversy.

Consumer products developed at such great expense to the ecosystem also have the unfortunate impact of degenerating into huge amounts of municipal solid waste.

Calculations of the total amount of municipal waste generated yearly, by the United States, exceed 10 billion tons. According to Nir (1990a), this breaks down into a United States per capita average of 3.5 pounds per day (p. 29).

According to Rathje and Murphy (1992), recent technological advances haven't changed an important truth about this garbage. Waste management procedures and practices haven't changed significantly for thousands of years. More importantly, much of what people consider common knowledge about the exact makeup of the solid waste product is mistaken. Product breakdown is crucially important in understanding the problems and opportunities that exist for solid waste recycling (one of the traditional ways of handling garbage) (Nir, 1990b; Rathje, 1989; Rathje & Murphy, 1992).

New state and federal landfill regulations governing all aspects of waste disposal will force the closure many existing sites and restrict the construction of all new ones. Up to 1200 municipal landfills are scheduled to close in the next five years and new sites are not being built to handle the volume of refuse (O'Leary, Walsh, & Ham 1988; Rivard, 1989).

The development of new composite materials which recycle discarded polyethylene plastic and agricultural fibers, and which provide a possible substitute for wood based building products is but one approach which attempts to address these ecological difficulties. The impact of land use policies on municipal landfills and federal timberlands are having unexpected and crucial interactions which will directly influence the feasibility and practicality of recycled waste materials.

The use of composite materials, as a substitute for traditional construction materials, has been and is a standard practice in the defense and aerospace industry. Recent cutbacks in defense spending and changes in the aerospace industry are forcing the composite industry into new product and process research and the development of new markets such as sports equipment, plastic posts, structural components and even plastic highway bridges (American Society of Metals, 1990; Ashley, 1991; Murray, 1990; Naitove, 1987; Plecnik, Henriques, & Deshpande, 1991; Pletcher, 1991; Rogers, 1991; Tortolano, 1990; Wehrenberg, 1985).

Trantina and Nimmer (1994) delineate a four stage design engineering process fundamental to the successful development of any engineering materials. These four stages are: stage one called the preliminary design stage, includes conceptual design, material, and process selection. Stage two, labeled engineering analysis, involves the proper selection of analysis tools, the generation of engineering data, and an understanding of possible process/material interactions. Stage three, designated detailed design, is concerned with part geometry and tooling. Stage four, classified prototype, is concerned with the fabrication and testing of design prototypes (p. 13-14). This study will focus mainly on the engineering analysis stage of the design engineering process which includes generation of engineering data about the innovative composite material made up of recycled polyethylene plastic and reinforcements made of agricultural fiber.

Statement Of The Problem

A part of that developmental process, according to Trantina and Nimmer (1994), requires an understanding of the interrelationships of materials, processing techniques, and product design capabilities. Plastics are complex high polymeric materials with amorphous structure producing a variety of mechanical properties that influence part performance. Reinforcements that are commonly added to polymers can affect the properties of the produced composites (p. 13).

Trantina and Nimmer (1994) assert that standard plastic data sheets do not provide properties that are directly useful for predicting the structural performance of plastic components (p. 13). A clearer understanding of the effect of distinct reinforcement materials, varied percentages of fiber reinforcement material in the plastic matrix, different fiber reinforcement lengths, and the effect of different temperatures on this product will allow the researchers involved in this project to determine the capability of this commodity to substitute for wood based structural building products.

Therefore, the problem of this study is to determine the effect of certain agricultural fiber reinforcements on tensile and impact mechanical properties of a recycled polyethylene plastic composite material.

Statement Of Purpose

The results of this study will provide the tensile and impact properties of a recently developed composite material, patented by Drs. Barton Bergquist and Mohammed Fahmy of the University of Northern Iowa. This composite material consists of a matrix of shredded recycled polyethylene plastic reinforced with agricultural filler fibers. Because of the lack of information about this material, the results of this study will provide vital information on the properties of this new composite. The variables under study are: the effect of the different types of fiber reinforcement, the effect of different percentages of fiber included in the matrix, the effect of different fiber lengths and the effect of different temperatures on the tensile and impact mechanical properties of this recycled shredded polyethylene composite material.

Statement Of Hypotheses

Hypotheses were established for this study based upon the fact that supportive data exists. The following hypotheses are made in regard to this study:

H_1: It is hypothesized that comparisons between the types of fiber reinforcement material will show a significant difference, at the .05 level, in the mean impact values as measured by American Society for Testing and Materials (ASTM) D 256-90b Standard Test Methods for Impact Resistance of Plastics.

H_{01}: It is hypothesized that comparisons between the types of fiber reinforcement material will show no significant difference, at the .05 level, in the mean impact values as measured by ASTM D 256-90b Standard Test Methods for Impact Resistance of Plastics.

H_2: It is hypothesized that comparisons between the percentages of fiber reinforcement material will show a significant difference, at the .05 level, in the mean impact values as measured by ASTM D 256-90b Standard Test Methods for Impact Resistance of Plastics.

H_{02}: It is hypothesized that comparisons between the percentages of fiber reinforcement material will show no significant difference, at the .05 level, in the mean impact values as measured by ASTM D 256-90b Standard Test Methods for Impact Resistance of Plastics.

H_3: It is hypothesized that comparisons between the temperatures of the test specimen will show a significant difference, at the .05 level, in the mean impact values as measured by ASTM D 256-90b Standard Test Methods for Impact Resistance of Plastics.

H_{03}: It is hypothesized that comparisons between the temperatures of the test specimen will show no significant difference, at the .05 level, in the mean impact values as measured by ASTM D 256-90b, Standard Test Methods for Impact Resistance of Plastics.

H_4: It is hypothesized that comparisons between the types of fiber reinforcement material will show a significant difference, at the .05 level, in the mean tensile strength, as a function of maximum fracture load and elongation, measured by ASTM D 638-90, Standard Test Method for Tensile Properties of Plastics.

H_{04}: It is hypothesized that comparisons between the types of fiber reinforcement material will show no significant difference, at the .05 level, in the mean tensile strength, as a function of maximum fracture load and elongation, measured by ASTM D 638-90, Standard Test Method for Tensile Properties of Plastics.

H_5: It is hypothesized that comparisons between the percentages of fiber reinforcement material will show a significant difference, at the .05 level, in the mean tensile strength, as a function of maximum fracture load and elongation, measured by ASTM D 638-90, Standard Test Method for Tensile Properties of Plastics.

H_{05}: It is hypothesized that comparisons between the percentage of fiber reinforcement material will show no significant difference, at the .05 level, in the mean tensile strength, as a function of maximum fracture load and elongation, measured by ASTM D 638-90, Standard Test Method for Tensile Properties of Plastics.

H_6: It is hypothesized that comparisons between the lengths of fiber reinforcement material will show a significant difference, at the .05 level, in the mean impact values as measured by ASTM D 256-90b Standard Test Methods for Impact Resistance of Plastics.

H_{06}: It is hypothesized that comparisons between the lengths of fiber reinforcement material will show no significant difference, at the .05 level, in the mean impact values as measured by ASTM D 256-90b, Standard Test Methods for Impact Resistance of Plastics.

H_7: It is hypothesized that comparisons between the lengths of fiber reinforcement material will show a significant difference, at the .05 level, in the mean tensile strength, as a function of maximum fracture load and elongation, measured by ASTM D 638-90, Standard Test Method for Tensile Properties of Plastics.

H_{07}: It is hypothesized that comparisons between the lengths of fiber reinforcement material will show no significant difference, at the .05 level, in the mean tensile strength, as a function of maximum fracture load and elongation, measured as measured by ASTM D 638-90, Standard Test Method for Tensile Properties of Plastics.

Limitations

Due to the nature of this study, and due to the restrictions of the resources and limitations of the facility being used, modification of ambient laboratory atmosphere to adhere to the specifications of the Standard Laboratory Atmosphere required in the test conditions section of ASTM D 256-90b and ASTM D 638-90 will not be possible. Therefore, adjustments in ambient temperature and relative humidity levels will not be considered in this study.

Delimitations

This study will be delimitated to the patented extruded agricultural fiber reinforced polyethylene plastic materials under study.

Assumptions

The following assumptions were made in pursuit of this study:

1. The methods and procedures utilized in preparation of the fiber reinforcement materials resulted in fibers that were passed through a .25, .75, and 1.50 inch screen and are uniform and consistent in average length.

2. The manufacturing and processing methods used to blend the fiber reinforcement material and the recycled polyethylene plastic resulted in a consistent and uniform mixture of fiber and plastic.

3. Test specimens selected, regardless of their position within the extruded composite plastic board construction two by four lumber, measuring approximately 3.5 by 1.5 by 74 inches, accurately represent the mechanical properties of those test specimens.

Definition Of Terms

The following terms are defined to clarify their use in the context of the study:

Advanced composite--A resin matrix material that is reinforced with high-strength, high-modulus fibers of carbon, aramid, or boron usually fabricated in layers (Cubberly & Bakerjian, 1989).

Composite material--A composite material is created by the combination of two or more materials--a reinforcing element and a compatible resin binder (matrix)--to obtain specific characteristics and properties (Cubberly & Bakerjian, 1989).

Extrusion direction--The direction in which the test specimens were extruded through the die relative to the microstructure of the samples.

Gage length--The original length of that portion of the specimen over which strain or change of length is determined (ASTM, 1991, p. 768).

Impact energy--The energy necessary to fracture a material (Parker, 1989, p. 943).

Impact load--A force delivered by a blow, as opposed to a force applied gradually and maintained over a long period (Parker, 1989, p. 943).

Impact strength--The ability of a material to resist shock loading (Parker, 1989, p. 943).

Impact stress--Force per unit area imposed on a material by a suddenly applied load (Parker, 1989, p. 943).

Impact test--Determination of the degree of resistance of a material to breaking by impact, under bending, tension and torsion loads (Parker, 1989, p. 943).

Mechanical property--A property that involves a relationship between stress and strain or a reaction to applied force (Parker, 1989, p. 1165).

Strain--the per unit change, due to force, in the size or shape of a body referred to its original shape or size. Strain is a nondimensional quantity, but is frequently expressed in inches per inch, metres per metre, or percent (ASTM, 1991, p. 769).

Stress--the intensity at a point in a body of the forces or components of force that act on a given plane through the point. Stress is expressed in force per unit of area (ASTM, 1991, p. 770).

Tensile strength--the maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried to rupture and the original cross-sectional area of the specimen (ASTM, 1991, p. 771).

CHAPTER 2

REVIEW OF LITERATURE

A comprehensive review of the literature related to agricultural fiber reinforcement of recycled polyethylene plastic is presented in this chapter. The material has been synthesized and presented under appropriate headings related to the literature. The chapter is divided into the following topics: (a) Composite Materials, (b) Design Considerations, (c) Manufacturing Factors, (d) Fiber Strengthen Composites, (e) Composite Structural Applications, (f) Agricultural Fiber Reinforcement, and (g) Summary.

Composite Materials

The field of composite materials is undergoing a period of unprecedented expansion and innovation. Rogers (1991) asserts that new composite materials, and innovative manufacturing processes are being developed which are expanding the influence of materials engineering into applications never before attempted.

A composite can be defined as a material made up of two or more phases that are usually processed separately and then bonded, resulting in properties that are different from those of either of the original materials tested alone (Flinn & Trojan, 1990, p. 648). This definition of composite materials is useful when describing the traditional composite construction materials.

Composite materials developed and/or desired by society, according to Flinn and Trojan (1990), can be grouped into three broad categories: traditional composites, synthetic composites, and advanced composites (see Table 1). Traditional composites (wood, asphalt, and concrete) compose the major part of all commonly used construction materials (Flinn & Trojan, 1990, p. 680). Although not normally thought of as composite materials, wood, asphalt, and concrete all meet the generally accepted definition of a composite material.

Categorized by Flinn and Trojan (1990), as macrocomposites, asphalt is seen simply as an organically bonded aggregate and concrete is defined as a mixture of paste and an aggregate. Essentially wood, is a fiber reinforced polymer whose properties are intimately related to its microstructure (pp. 680-681).

Synthetic composite materials can be distinguished from other composite materials in that the composite structure is built by selecting the nature, amounts, shapes, and sizes of the different materials and then bonding them together in a controlled orientation (Flinn & Trojan, 1990, pp. 648-649; Smith, 1993; Strong, 1989). Categorized as microcomposites, examples of synthetic composite materials are fiberglass, cemented carbides, graphite-epoxy, and kevlar-epoxy.

Table 1

Categories of Composite Materials

Macrocomposites	Microcomposites	Advanced Composites
Asphalt organically bonded aggregate Concrete mixture of cement and aggregate Wood fiber reinforced natural polymer	Synthetic Composite built by selecting the nature, amounts, shapes and sizes of the different materials , then bonding them together in a controlled orientation	Structural Composites blends of two or more materials--usually a long stiff fiber and a resinous binder or matrix--designed to replace traditional structural load bearing members

Advanced composite materials, sometimes referred to as modern structural composites, are blends of two or more materials, one of which is composed of stiff, long fibers, and for polymeric composites, a resinous binder or matrix, which holds the fibers in place (Cameron, 1988; English, 1989; English, 1990; Peters, 1992, p. 5.1; Pollock, 1988, p. 505; Tortolano, 1990).

According to Peters (1992), the commercial availability of fiberglass filaments in 1935, the development of strong aramid and carbon fibers in the late 1960s and early 1970s, and the promulgation of analytical methods used for designing and testing the structures made from these fibers were all crucial advances necessary in the development of these materials (p. 5.1). Although some ceramic composites existed in the 1920s, according to Strong (1989), the first modern application of composites was in 1945 and was a glass-reinforced phenolic-nylon fishing pole (p. 2). Modern products made from composite materials include medical, automotive, machine tools, recreational, industrial, and commercial aircraft products (Tortolano, 1990, p. 52).

Advanced polymer matrix composites have been slow to adapt to high volume industrial applications due to high production and material costs. The capability to engineer or customize the mechanical properties of the composite or engineering plastic to a specific application are opening many new markets to composite manufacturing. Products developed using synthetic or advanced composite materials include orthopedic implants, a prosthetic foot, rollerblade skates, composite skis, bicycles, baseball bats, golf clubs, athletic shoes, softer footballs, gear selector forks for race cars, jet engine vanes, machine tooling, construction reinforcements and structural construction materials (Ashley, 1991; Cameron, 1988; Murray, 1990; Nastali, 1985; Rogers, 1991; Tortolano, 1990).

Design Considerations

The process of developing a new product concept into a commercial commodity is a dynamic and challenging process. The advances in engineered plastics and composite materials have presented the design engineer with many advantages. So favorable are these materials that a noticeable usage trend has occurred (Boggs, 1988).

Product Design

Designing products with composite materials is not as easy or as simple as conventional product design. According to Sundaresan (1988), the traditional design techniques utilized in conventional product development are inadequate to the task of composite product design. Sundaresan contends that using composite materials, instead of conventional metals and alloys, results in added variability and complexity in the design and manufacturing processes. Because the design techniques involved with composites materials are revolutionary rather than evolutionary, Sundaresan (1988) points out that many design engineers are uncomfortable with composite product design because they are unable to apply standard conventional properties to the innovative products being developed (p. 75). This inability of the design engineers to obtain off-the-shelf properties is also made worse by the fact that the constituents of many composites are not clearly stated.

Edwards (1989) asserts that the capability of fabricating products with specific mechanical and physical properties makes the design process for composite materials very different than that used in metals (p. 16). Significant changes in composite manufacturing techniques have necessitated the need to utilize concurrent engineering during the design process so that the product is designed with the manufacturing process in mind. Certain manufacturing and design parameters, such as, component geometry, production volumes and rates, reinforcement type and orientation, matrix type, proportion of matrix to reinforcement (fiber volume fraction percentage), tooling requirements and economics must be considered simultaneously.

Other factors are also influencing the process by which a product is developed and marketed. Rapid technological change in new materials, process refinements and customer requirements are dictating a greater understanding of the interactions and interrelationships of the various processes embedded in a manufacturing organization. These interrelationships directly affect product quality and cost, manufacturing requirements, processes and operations (Cubberly & Bakerjian, 1989; Rudd, 1992).

Design For Recyclability

Societal and ecological consideration also having a major impact on composite manufacturing is the increasing public debate about resource conservation, solid waste landfill policies, potential environmental legislation, and the issue of plastics recyclability (Baker, 1991; Bell, 1990; Lantos, 1990; Leventon, 1992).

Baker (1991) contends that design engineers are addressing this concern by modifying the design and product development process to incorporate environmental considerations. A concept such as design for recyclability is being increasingly incorporated in all new product development.

Many of these recent changes in the design and development process have been formulated to affect the problem of plastics refuse. Recent estimates indicate that about 57 billion pounds of plastic were produced in the United States in 1988. Figures also indicate that only between six and ten percent of this amount of plastic was recycled during that year (Lantos, 1990; Leventon, 1992). Research into the volume amount of nonrecycled plastics in solid waste landfills indicate that about 16% of the total volume is plastic materials (Nir, 1990; Rathje, 1989; Rathje & Murphy, 1992). Barriers to increased recycling, according to Bell (1990), are limited by economic factors which have prevented the development of three conditions necessary for successful recycling: large-scale reclamation, the development of new products, and mass markets for these products (p. 944).

Changes in society, manufacturing technology, and the ecology are having direct and indirect effects on the potential marketability of composite materials. The opportunities available for engineered materials, especially those which recycle existing refuse plastic, are dependent on the design process which incorporates the advantages of lower cost, greater creativity, and ease of production. This new societal and ecological consideration triggered this point of research.

Manufacturing Factors

Naitove (1987) contends that this is a period of new technology development for fiber-reinforced thermoplastic and thermosets, whether for the high-tech aerospace or for commercial/industrial markets in automotive, marine, and mechanical goods (p. 79). The development of new products from composite materials is dependent on improvements in the manufacturing technology being utilized in the fabrication phase of composites process.

The composites industry has had to cope with requirements for improved mechanical properties and economical manufacturing techniques. When compromise has had to occur, the traditional choice has been to sacrifice economics rather than any mechanical or physical property (Peters, 1992).

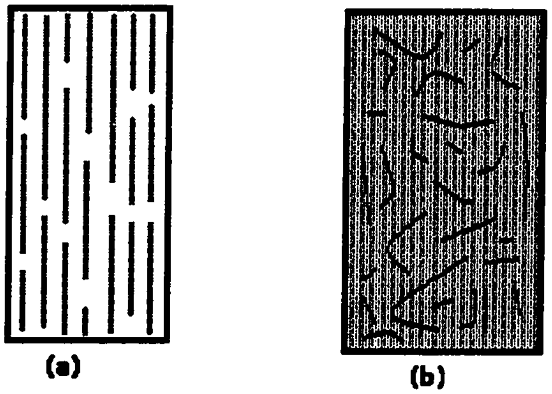
Strong (1989) agrees that this procedure has allowed the mechanical properties of the chosen composite materials to vary according to the physical properties needed for a specific application. This sometimes has required compromises between the ideal manufacturing method and the optimum mechanical properties of the chosen material (p. 107).

The goals of any composite manufacturing process are: (a) to achieve a consistent product by controlling fiber thickness, (b) regulate fiber volume and direction, (c) minimize voids, (d) reduce internal residual stresses, and (e) process the product in the least costly manner (Peters, 1992, p. 5.31). To achieve these goals crucial decisions must be made in regard to three key components: composite material, tooling, and process (Peters, 1992, p. 5.31).

According to DeGarmo, Black, and Kohser (1988) the most popular type of composite material is fiber-reinforcement geometry, as illustrated in Figure 1, in which continuous or discontinuous thin fibers of one material are embedded in the matrix of another (p. 195).

Research indicates that the key to realizing the full potential of these materials is in the proper use of a variety of fibers and fabrics to reinforce the thermoplastic or thermoset matrix. The economics and performance of these composite materials, for any specific application, is dependent on an understanding of: molecular configuration of the polymers used, fiber properties, fabric form and arrangement, and fabrication method used (Budinski, 1983;

English, 1985, 1989; Kardos, 1984; Margolis, 1988, p. 65; O'Connor, 1986).



Variations in fiber distribution. (a) Continuous or nearly continuous fibers. (b) Discontinuous or chopped fibers.

Figure 1. Variations in fiber distribution.

DeGarmo et al. (1988) expand this proposal by listing the following characteristics that are considered as strong influences on the physical properties of any composite material: the properties of the fiber material, the fiber volume, the aspect ratio of the fibers, the orientation of the fibers, the degree of bonding between the fibers and the matrix, and the properties of the matrix (p. 196).

The properties of the fiber material utilized might include such problems as weak interfacial adhesion between the polymers and the reinforcement filler, a poor dispersion of the filler material in the matrix, and poor wettability of the fiber surface with the plastic matrix. Research by Maldas and Kokta (1990, 1991) indicate that these problems might be solved by surface treatments of the filler material.

Research by Springer, Wang, and McCleary (1994) has indicated the importance of the fiber arrangement within the matrix. Tests on unidirectional, triaxial and random fiber arrangements, in both tension and compression, indicate that continuous unidirectional fibers provide the largest increase in performance improvement. Noncontinuous unidirectional fibers provided the next best performance enhancement followed by a triaxial fiber arrangement and finally random orientation. The random arrangement also demonstrated a greater tendency for matrix failure due to increased crack propagation.

English (1989) contends that to maximize the mechanical properties of most discontinuously reinforced composites the number or volume of the fibers should be as low as possible to minimize internal crack initiators. English indicates that while the fibers themselves are strong and stiff, the ends of the fibers act as notches which concentrate stresses and possibly initiate a crack in the matrix under load (p. 35).

Gibson (1994) states that fiber volume fraction and fiber length are limiting factors in improving the performance of any composite material. Improvements in mechanical properties occur until a critical fiber volume fraction and/or a critical fiber length are reached. Strength improvements do not occur if additional fiber volume is added to the matrix or if the critical fiber length is exceeded (p. 117, 160-161).

Research by Chow and Lu (1991) indicate that a lot of composite materials are inherently anisotropic in nature. They contend that applying traditional mechanics theories to these materials present certain analysis obstacles but also stated that careful design and fabrication techniques can minimize these problems.

Wang, Jang, Panus, and Valaire (1991) recognize the importance of improving and controlling the specific properties of a hybrid composite but suggest that the composite material might not provide expected or predicted results. Analysis techniques utilizing both static properties and impact resistance were suggested for a better understanding of the fiber/matrix interactions. Swanson (1993) suggests that the specific impact test utilized, either quasi-static or dynamic impact loading will generate calculated strains that are quite similar.

The selection of a common industrial thermoplastic like polyethylene for this research project was a recognition of the advantages and realities of the current technology. Polyethylene is by far the most extensively used plastic material, accounting for 32% of plastic sales in the United States in 1988. Polyethylene plastic products are light weight, low cost materials with outstanding chemical resistance, good toughness, and have excellent dielectric properties. More importantly, the basic properties of polyethylene can be easily modified with a wide range of fillers, reinforcements, and chemical modifiers. In addition, polyethylene is easily processed by injection molding, extrusion, blow molding, and rotational molding (Brady & Clauser, 1991, p. 652; DeGarmo et al., 1988, p. 179; Peters, 1992; Smith, 1993, p. 308).

Tooling and process considerations are dependent upon the specific application envisioned for the composite material. The versatility and adaptability of the extrusion process of plastic and composite fabrication limits tooling costs but still allows a wide variety of varied applications. It is especially popular as a manufacturing technique for products requiring long dimensions in one axis such as composite building materials (DeGarmo et al., 1988; Neely & Kibbe, 1987, p. 346).

Fiber Strengthened Composites

Fiber strengthen composite materials, whether macrocomposites, microcomposites or advanced composites, are dependent upon the interactions of the matrix material and the fiber reinforcement. Granet (1980) states that the basic principal used in fiber strengthened composites is that materials are generally stronger in fiber form than in bulk form (p. 342). The principal role of the fiber reinforced matrix is then to transfer the stresses on the material to the main load bearing part of the composite, the fiber reinforcement material.

For effective fiber reinforcement material, the modulus of elasticity of the fiber (E_f) has to be much greater than that of the matrix (E_m). The amount of fibers in the composite material (fiber volume fraction percentage) must also be maximized to achieve the greatest possible composite load bearing capacity. Too many reinforcement fibers embedded in the matrix will decrease strength due to the inability of the matrix to properly coat the fibers, resulting in poor bonding. Too few fibers will result in a decreased load bearing capacity due to ineffective matrix fiber interactions (Granet, 1980, pp. 342-343). This relationship can be mathematically described so that the modulus of elasticity of the composite depends on the modulus of elasticity of the reinforcement material and its fiber volume fraction percentage ($E_c = E_f V_f$).

The literature indicates that, among the possible treatment variables inherent in composite materials, fiber orientation has a greater impact on composite strength than does fiber length (Gibson, 1994; Granet, 1980; Harper, 1992; Strong, 1989; Trantina & Nimmer, 1994). It is taken for granted that, under load, some of the reinforcement fibers will fracture. This fracturing of the reinforcement fibers is not of critical importance because the soft matrix will inhibit the any propagation of the resultant crack. An additional obstruction to the propagation of any crack is that the fractured fibers will not have failed in the same plane thus preventing coordinated movement (Granet, 1980, p. 343).

Short discontinuous fibers transfer the load to matrix at the fiber ends. Fiber strength is not as developed at the ends of the fiber when compared to the entire fiber and a decrease in strength is realized. For maximum fiber stress capacity, a critical fiber length must be achieved. Mathematically, this can be computed with the following formula:

$$\frac{l_c}{d_f} = \frac{S_{fmax}}{2(S_s)_m}. \qquad (1)$$

where l_c indicates critical fiber length, d_f is the diameter of the fiber, S_{fmax} is maximum fiber stress, and $(S_s)_m$ is the shear stress of the matrix.

Randomly oriented fiber reinforced composites have less load bearing capability than controlled orientated fiber reinforcement composites due to the random nature of the fiber matrix interface. This results in an averaged value for Young's modulus, shear modulus and Poisson's ratio. The formulas for these properties are for averaged Young's modulus for randomly oriented fiber composites,

$$\bar{E} = \frac{E_f V_f}{3} . \qquad (2)$$

for averaged shear modulus for randomly oriented fiber composites.

$$\bar{G} = \frac{E_f V_F}{8} . \qquad (3)$$

and the averaged Poisson's ratio for randomly oriented fiber composites.

$$\tilde{V} = \frac{1}{3}. \qquad (4)$$

Understanding the various stages or mechanisms of deformation will explain why randomly oriented discontinuous fiber composites are so different in mechanical properties when compared to oriented continuous fiber composites. According to the literature, a continuous fiber reinforced composite, stressed in the direction of the fibers, will fail in the following four stages:

> 1) Both the matrix and fibers deform elastically under load;
>
> 2) Additional load causes the matrix to reach its yield strength. The matrix deforms plastically while the fibers continue to act elastically and take up the greater fraction of the load;
>
> 3) The continued increase in loading causes the fibers and matrix to both deform plastically;
>
> 4) Any further increase in load will cause the fiber to fracture and cracks will propagate across the matrix leading to failure of the composite. (Granet, 1980, pp. 343-344)

Randomly oriented fiber composites, especially those with a heterogenous nature, will exhibit elastic and plastic deformations occurring simultaneously dependent upon matrix fiber interactions and the loading aspect of the fibers. When compared to continuous fiber reinforced composites, randomly oriented fiber reinforced composites show an approximate decrease in Young's modulus by 66%, a decrease in shear modulus strength by 88% and an average Poisson's ratio of 1/3. While fiber length and fiber volume fraction percentage are important variables to consider, fiber orientation is obviously the most significant manufacturing variable.

Composite Structural Applications

Advances in manufacturing technology and design techniques have opened the possibility for increased use of composite materials for structural applications. According to Pletcher (1991), structural composite materials can offer advantages of thermal stability, high strength and stiffness-to-weight ratios, inherent corrosion resistance, superior thermal insulating qualities, impact resistance, and durability (p. 44). Plecnik et al. (1991) state that certain composites, known as fiber-reinforced plastics (FRPs), have widespread applications as replacement construction materials for bridge construction, bridge cables, and bridge decking. Minosaku (1992) asserts that the corrosion resistance characteristics of FRPs make that material especially useful as reinforcing materials for concrete and soil structures, prestressed tendons, and tie materials in port and harbor structures, and pretensioned strands in pedestrian and highway bridges (pp. 42-44).

The Japanese Ministry of Transportation, the Japanese Railways Company, the Japan Society of Civil Engineers, the

United States Federal Highway Administration, California State University-Long Beach, and the American Society of Civil Engineers have all launched joint and/or independent studies into the potential application of FRPs as structural replacement materials (Childs, 1989; McCormick, 1988; Minosaku, 1992; Plecnik et al., 1991).

Figures released from the Reinforced Plastics Composites Institute of the Society of the Plastics Industry (SPI) indicate that this process of using alternate construction materials has been a growing trend for many years. Shipments of FRPs to construction markets showed an increase, in 1984, of 28% over 1983. Additionally, shipments of FRPs to consumer markets were up 52%, appliance/business equipment were up 29%, corrosion resistant applications were up 23% and land transportation applications were up 28% (American Society of Metals, 1990, p. 20).

The concept of building structures with alterative FRP materials is still finding increased applicability as time passes. Japanese engineers are considering the applicability of FRPs for use in offshore structures and magnetic levitation trains (Minosaku, 1992, p. 41).

Agricultural Fiber Reinforcement

Agricultural fibers exhibit a randomness and uniqueness that has limited their use in composites. Composite manufacturers have wanted a uniformity and degree of control that isn't possible using naturally grown materials. Changing circumstances and economics have spurred research into this area by American and Japanese scientists.

The role of the reinforcement material is, according to Wood (1984), becoming more important and apparent with each year. The reinforcement can reduce the cost factor without hampering productivity and performance and many do much more than that (p. 51).

Changing manufacturing technology and innovations in FRP fabrication processes have dramatically opened up the possibilities for unconventional filler reinforcements and many new types of thermoplastics. One area generating considerable interest is in organic fiber reinforcement materials.

Two approaches to organic reinforcement materials have developed in the last few years. Giant chemical companies such as Du Pont and Allied Corporation are developing artificial organic fibers such as high strength graphite, Spectra 900, and high modulus graphite (Monks, 1991; Wehrenberg, 1985, pp. 60-62).

The alternative approach to artificial organic reinforcement materials has been the application of natural organic materials such as corncobs, vegetable fibrous materials, cellulosic fibers, and biomass (stalks from various grain products). Juran (1985) claims that the farms of the Middle West provide an almost limitless supply of biomass materials estimating corncob supplies at almost 80 billion pounds (p. 52).

Mobil Chemical Co. has recently formed a new Composite Products Division to help promote a polyethylene film and cellulose recycling process. The process produces a wood composite, called Timbrex, by recycling shredded polyethylene film and finely ground sawdust. Mixed in a custom built mixer/dryer, the resulting clay like compound is extruded through a die to form a 2 x 4. Mobil produces about 10 million pounds of lumber per year and plans to expand production to three additional plants (Staff, 1993, p. 94).

Interest in composites materials utilizing biomass products (wheat stalks, graminaceous rice products, vegetable fibrous materials, cellulose materials and recycled waste plastics) have resulted in numerous patents to both foreign and American innovators. In 1974, United States Patent (#4,013,616) was issued to Richard C. Wallace for a structural material made from waste residue and polymeric materials. In 1980, the United States Patent Office issued a patent to Teresio Signoretto (#4,202,803) for a vulcanized rubber product utilizing biomass fillers. Patent (#4,203,876) was issued to Michael Dereppe and Jean Leva, in 1980, for a moldable thermoplastic composite material containing vegetable fibrous materials and synthetic elastomers. United States Patent (#4,559,376) was issued to Josef Kubat and Tore C. F. Klason, in 1985, for a method for producing plastic composites with cellulose fiber fillers. A similar composite material made from thermoplastic resin and cellulosic fiber fillers was issued a patent (#4,822,826) in 1989. Recently Barton L. Bergquist and Mohammed F. Fahmy were awarded a patent (#5,194,461) for a production method and structural construction material developed from recycled high density polyethylene and herbaceous fibers.

A recent article in a trade journal published by Deere & Company (a leading farm implement manufacturer) indicates an excellent potential for such products. According to Kessler (1994), efforts are underway to produce various FRP composite products from biomass materials and recycled plastics. Product applications include boards, posts, furniture, insulation panels, and playground equipment (p. 22).

Kessler (1994) indicates that the first products being developed are standard construction shapes like 2x2s and 2x4s which will be used in place of the traditional wood construction materials. Contracts for sign posts for state highway departments, building materials for use in wet or damp conditions, and substitutes for increasingly expensive wood products all are potentially profitable markets for these agricultural reinforced composite materials.

Summary

In summary, composites manufacturing technology is a process with a long and varied history covering thousands of years. With recent changes in society, many people are rediscovering and reexamining this technology. A lack of experience and reliable information in regard to design considerations, conventional property data characteristics, manufacturing variability, manufacturing capability, manufacturing economics, and basic material science have all restricted the applicability of composite materials to a limited number of uses. These problems can be overcome with increased efforts in applied research on specific composite materials such as the materials under study in this project.

CHAPTER 3

RESEARCH METHODOLOGY

The general methods and procedures utilized for this study are described in this chapter. The information will be presented under the following chapter headings: (a) Preliminary Research, (b) Experimental Procedures, (c) Fiber Preparation, (d) Fabrication Process, (e) Impact Testing Procedures, (f) Tensile Testing Procedures, (g) Process/ Material Interactions, and (h) Statistical Analysis and Data Presentation.

Preliminary Research

The author failed to find any published literature related to the filler material under consideration. However Flinn and Trojan (1990) presented a summary of similar reinforcement materials and their effects on property characteristics. Materials listed in this analysis included asbestos, calcium carbonate, carbon fiber, cellulose, alpha cellulose, cotton (macerated/chopped fibers), fibrous glass, fir bark, nylon, orlon, rayon, and wood flour. Based on this information on chopped cotton fibers, property improvements occurred in the areas of electrical insulation, impact strength, tensile strength, dimensional stability, stiffness, and hardness (Flinn & Trojan, 1990, p. 618).

Preliminary tests conducted on the composite materials under study during the patent application process showed that the differences in testing temperature, type of reinforcement fiber, and fiber volume fraction percentage affected the breakage energy determined by a standard Izod notched impact test.

Notch impact tests performed during the patent application process were conducted on randomly oriented agricultural fiber reinforced polyethylene composite materials. Tests were performed at three temperatures (49^0, 23^0 and - 196^0 Centigrade (C)), on four different fiber reinforced test samples (a control sample with no reinforcement material, oatstraw, soybean stalks, and corn stalks fiber reinforcement material), and at four different fiber volume fraction percentages (10, 20, 30, and 40 percent).

Preliminary test data for tests conducted at ambient room temperature (23^0 C) indicated a noticeable improvement in fracture load with the incorporation of reinforcement fibers (see Figure 2). This improvement in the impact fracture load required to break each notched specimen changed differently with different reinforcement fibers, and different fiber volume fraction percentages. In regard to this test, all fiber reinforcers were identically prepared and had approximately the same fiber length.

A control specimen, at 23^0 C, made up of 100% polyethylene plastic absorbed impact energy of 3.48 Joules/Second (J/S) before fracture occurred. The addition of oatstraw, as fiber reinforcement, resulted in a gradual increase from 3.48 J/S to 3.73 J/S impact energy with approximately 10% fiber reinforcement, and to 4.72 J/S with approximately 20% fiber reinforcement. A dramatic increase to 13.42 J/S occurred as 30% fiber reinforcement was added. This would indicate that the impact strength was increased up to at least a fiber volume fraction percentage, for oatstraw, of 30%.

The addition of soybean stalks as the reinforcement material showed even more striking improvements. The incorporation of approximately 10% fiber reinforcement resulted in a improvement of 369% with fracture loads increasing from 3.48 to 12.83 J/S. The augmentation of the test specimen with additional fiber reinforcers to 20% resulted in an additional impact strength improvement to 13.22 J/S. A decrease in fracture strength occurred when 30% reinforcement fiber was used as notched impact strength decreased to 12.87 J/S. This suggests that the optimum fiber volume fraction percentage for soybeans would be between 20 and 30%.

The use of cornstalks as a reinforcing material demonstrated even more conspicuous initial impact improvement and a distinctive decrease in strength unique to this materials. A 421% improvement in impact fracture load occurred when 10% cornstalk fiber reinforcers were utilized jumping from 3.48 to 14.67 J/S notched impact strength. Additional increases in fiber volume fraction percentages resulted in decreased notched impact strength. Fiber percentages of approximately 20, 30, and 40% resulted in, respectively, 10.39, 8.05, and 7.23 J/S of notched impact strength. Clearly, the optimum fiber volume fraction percentage for corn was around 10%.

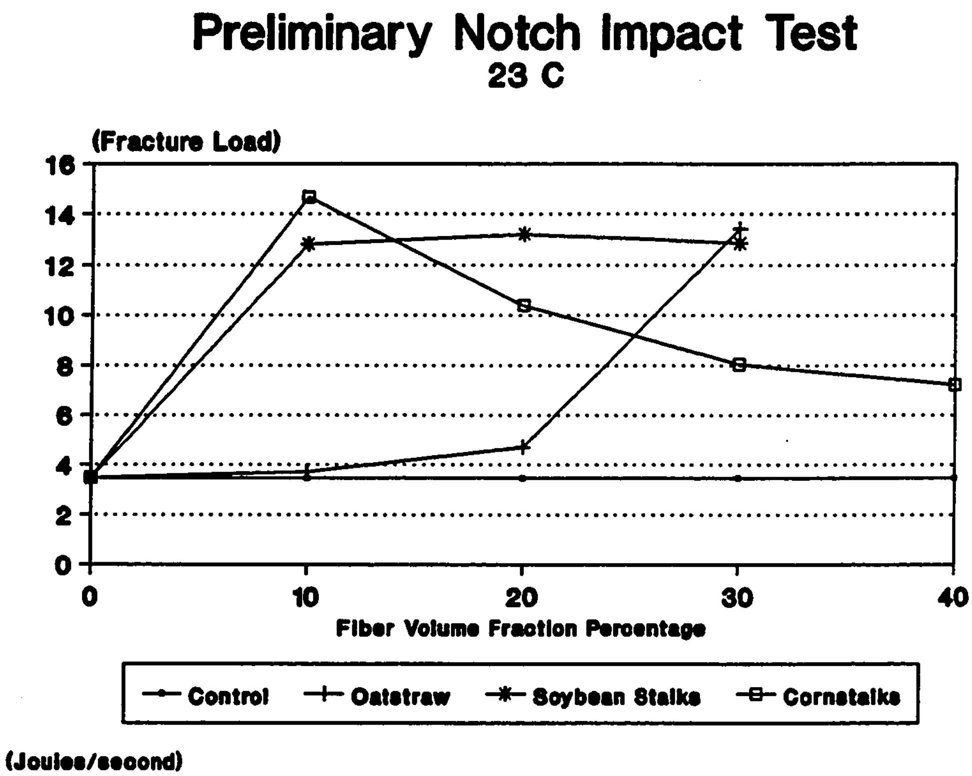


Figure 2. Preliminary notch impact results (23^0 C).

Impact fracture load tests were also conducted at temperatures of 49^0 C and - 196^0 C. As this composite material was being considered for use as a building materials substitute for wood, these tests were used to simulate the effects of hot and cold weather. The effect of cold temperatures, on this specific composite material, were quite noticeable (see Figure 3).

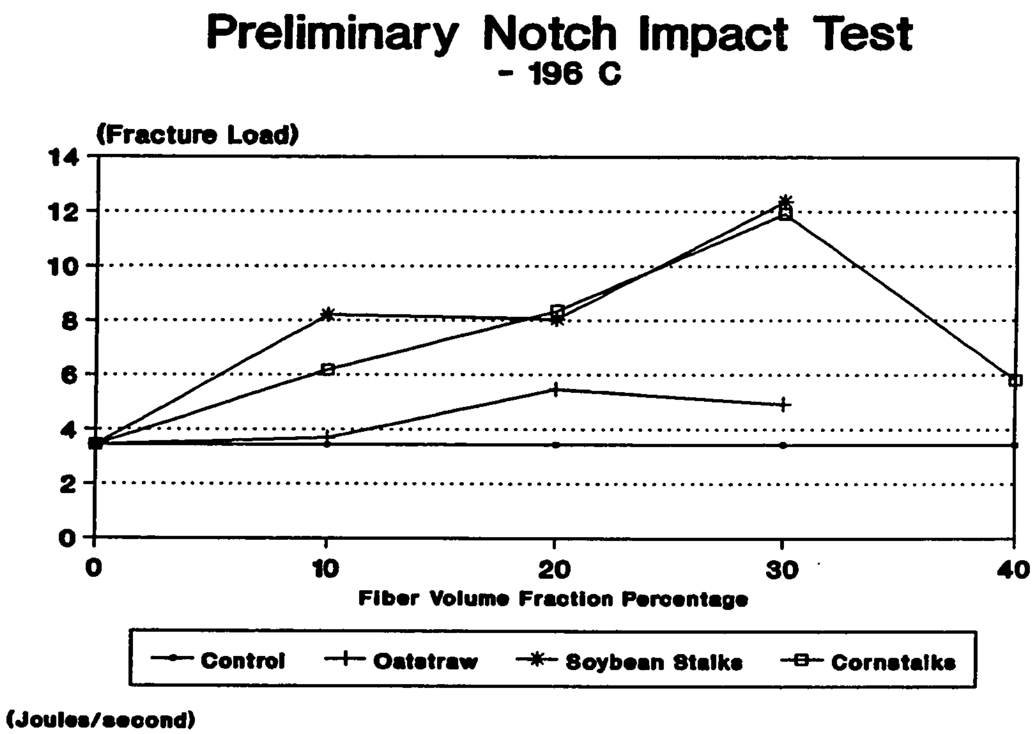


Figure 3. Preliminary notch impact results (- 196^0 C).

Dramatic decreases in impact fracture load strength were evident, during the - 196^0 C test, regardless of the fiber reinforcement material. A fiber volume fraction percentage of approximately 10%, regardless of fiber type, resulted in an increase in fracture impact strength when compared to the control sample. A oatstraw reinforced composite material increased in notched impact strength from 3.45 to 3.7 J/S. Increases in fiber reinforcement to approximately 20% increased notched impact strength to 5.46 J/S. Additional fiber reinforcement to 30% resulted in an additional decrease of notched impact strength to 4.92 J/S. This data would indicate that under cold conditions, the optimum fiber volume fraction percentage for oatstraw reinforced composite material would be approximately 20%.

Composite materials reinforced with soybean stalks and cornstalks showed very similar material characteristics. Both composites had increased impact strengths at the 10% reinforcement level. Soybean composites increased in impact strength nearly 138% with an increase from 3.45 J/S to 8.2 J/S. Corn increased 79% in impact strength raising from 3.45 J/S to 6.17 J/S. After this increase both materials evidenced either a minor decrease followed by an increase (soybeans) or steady improvements (cornstalks) up to 30% fiber reinforcement. Soybeans and cornstalk composites demonstrated maximum notched impact strength at 30% fiber reinforcement with readings of 12.38 and 11.93 J/S respectively. The addition of more fiber reinforcement material to the cornstalks samples resulted in a decrease in notched impact strength to 5.82 J/S. This would indicate that the optimum fiber volume fraction percentage for both soybean and cornstalks reinforced composites would be approximately 30%.

Tests conducted at elevated temperatures (49^0 C) showed both increases and decreases in notched impact strength. Both soybean stalk and cornstalk reinforcements demonstrated increased fracture strength in the lower reinforcement percentages (see Figure 4). Cornstalk and soybean stalk fiber reinforcement at the 10% level increased fracture strength from 12.38 J/S to 13.87 and 13.27 J/S respectively. Oatstraw reinforcement at the 10% fiber level produced dissimilar results. A decrease in fracture strength of approximately 45% occurred when the oatstraw samples were tested dropping from 12.38 to 6.79 J/S.

Oatstraw composites with additional reinforcement material at the 20% fiber volume fraction percentage level exhibited improved fracture strength with a reading of 12.38 J/S. Cornstalk and soybean stalk composites peaked in notched impact strength at the 10% reinforcement level and declined to 12.53 and 11.63 J/S, respectively, at 20% fiber reinforcement.

Additional fiber reinforcement beyond 20% resulted in decreased fracture strength levels for all composite materials. Oatstraw composites declined to 9.4 J/S notched impact strength at the 30% level while soybeans declined to 10.89 J/S and cornstalks dropped to 8.35 J/S. Cornstalks notched impact strength further declined when tested at 40% fiber volume fraction percentage to a reading of 7.61 J/S.

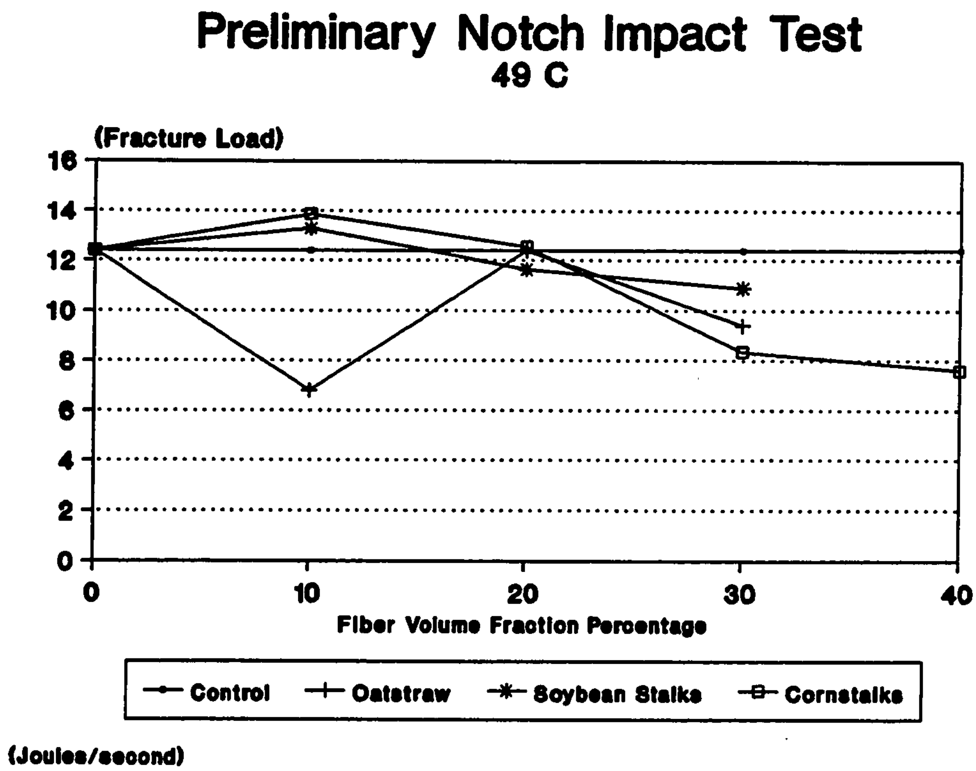


Figure 4. Preliminary notch impact results (49^0 C).

This data indicates that both cornstalk and soybean stalk reinforced composites had improved fracture strength compared to a non-reinforced control sample. The optimum fiber volume fraction percentage for each is approximately 10%. Oatstraw reinforced composites did not exhibit improved fracture strength. At the 20% fiber reinforcement level, the oatstraw samples tested performed as well as the control sample. At any other reinforcement level, the oatstraw samples displayed reduced fracture strength performance.

This preliminary research into the composite material under study indicates the importance of further testing to develop a better understanding of the mechanical properties of this material. Any other research into other filler materials is beyond the scope of this study.

Experimental Procedures

In analyzing the mechanical characteristics of a composite material, the researcher is by circumstances limited to three types of tests: standard tests (used when applicable), nonstandard tests (used when no standard tests are found), and prototype and model tests for product development. According to Prosen (1967), the first two types of tests give data on materials comparisons and are used in research and development work. The last type provides the design data needed for specific applications (p. 159).

The development of engineering data for a composite material, especially for a material designated as a substitutional product, requires that the element under study be readily comparable to the original substance. This limits the necessary testing procedures to standard or nonstandard tests. There are two main sources of standard tests: The American Society For Testing and Materials (ASTM) and Federal Specifications. There are more than 25 mechanical test methods listed for reinforced plastics (Prosen, 1967, pp. 159-160).

Selecting the appropriate test(s) requires an understanding of the limitations of those tests. Many of these standards have been in existence for many years and are adapted from standards used with metals. Testing reinforced plastics, contends Prosen (1967), using these tests has some inherent traps and pitfalls. Tests developed for metals rely on the fact that they are isotropic and homogenous materials. Composite materials of all types are anisotropic and heterogeneous. Therefore, careful selection of the proper tests and a understanding of the possible process and material variability, inherent when applying the engineering data to results and/or conclusions, is vital (Prosen, 1967; Strong, 1989; Trantina & Nimmer, 1994).

Research by Lokshin, Gurvich, and Perov (1990) indicate the importance of having information on the strain properties of any composite material in order to evaluate product reliability and establish safety factors. Two of the fundamental mechanical properties that play an important role in the engineering design process, for lumber material, are structural stiffness and impact resistance (Trantina & Nimmer, 1994). In this study the ASTM standard test methods and analysis procedures outlined in ASTM D638-90 (Standard Test Method for Tensile Properties of Plastic (Metric), ASTM D 256-90b (Standard Test Methods for Impact Resistance of Plastics and Electrical Insulation), and ASTM D790-90 (Standard Test Methods for Flexural Properties of

Unreinforced and Reinforced Plastics and Electrical Insulating Materials) were utilized. The Applied Systems, Inc. Series 900 Universal Testing machine, was used for testing the static mechanical properties of the composite material under study. An Izod notch impact tester was used to conduct the impact tests. The only variation from ASTM procedures occurred during the flexure tests. Due to a limited amount of test material, multiple testing for each sample was not possible.

The experimental design flow charts of the test program used in this study are presented in Appendix A. The flowcharts for these tests also show the variables being tested. For the impact test, variables such as fiber type (oatstraw or soybean stalks), approximate fiber volume fraction percentage (25 or 30%), approximate fiber length (0.64, 1.91 and 3.81 centimeters) and treatment temperature (23^0, 60^0 and - 196^0 Centigrade).

For the tensile tests and flexure tests, the flowchart indicates that the variables being tested are identical as the impact tests except that the temperature variable has been eliminated.

Fiber Preparation

This study represents the effects of two different agricultural fiber reinforcements, three different fiber lengths, two different fiber volume fraction percentage, and three different temperatures on the notched impact strength, and/or tensile strength of recycled polyethylene plastic. The agricultural fibers used in this study are oatstraw and soybean stalks. Fiber lengths tested are approximately 0.64, 1.91 and 3.81 centimeters (as maximum lengths in each category). All fibers were delivered to the researcher in bales. A commercially available tree limb shredder (Rotohoe Cut'n Shred Shredder Model 800CP) was used to chop the fibers into the desired lengths by passing the fibers through screens with hole diameters of 0.64, or 1.91, or 3.81 centimeters.

During the chopping process, care was taken so that each fiber type and fiber length was kept separated from the others. Contamination of the fiber by rocks, dirt, water, or other materials was not allowed. After chopping, the fibers were placed in plastic bags to await shipment to the industrial manufacturing site for inclusion in the extruded lumber samples under investigation.

Fabrication Process

This study generated data about the effects of various types, lengths, and two percentages of fiber reinforcements on the impact, tensile, and flexure strengths of extruded construction lumber size 3.81 by 8.23 by 188 centimeters (commonly known as 2 x 4s).

This required the manufacture of 12 composite lumber boards and a single control of nonreinforced polyethylene plastic used as a reference. Test boards were produced for each of the two randomly distributed fiber types (oat straw and soybean stalks) with different but specified amounts of filler fiber volume fractions (approximately 25 and 30%) and for each of the specified fiber lengths (0.64, 1.91 and 3.81 centimeters). The prototype composite lumber boards were manufactured by Hammer's Plastic Recycling Corporation of Iowa Falls, Iowa. The lumber was composed of recycled polyethylene plastic, formerly used in the manufacture of milk jugs, and agricultural fibers.

Due to manufacturing variables and processes, exact filler fiber percentages are difficult to achieve. Adequate random distribution of the fiber throughout test specimens was accomplished by the normal mixing process associated with the extrusion process used in industry. The extrusion process was chosen because it is one of most commonly used manufacturing method used for thermoplastics. Moreover, products manufactured by this process can be made into a variety of shapes and products. Furthermore, the extrusion process has been proven useful in the reclamation of scrap thermoplastic materials. In manufacturing this lumber, recycled thermoplastic materials, and the reinforcement materials, were fed into a heated cylinder and the molten plastic was forced through a die opening to form the continuous shape wanted. No attempt was made to control or direct the orientation of the fiber reinforcement.

The lumber used was produced by a conventional extrusion process (as illustrated in Figure 5) using a standard die. No special tooling or dies were required in the manufacture of the specimens. Conventional industrial conditions were used and no special precautions were utilized during the manufacturing of the lumber.

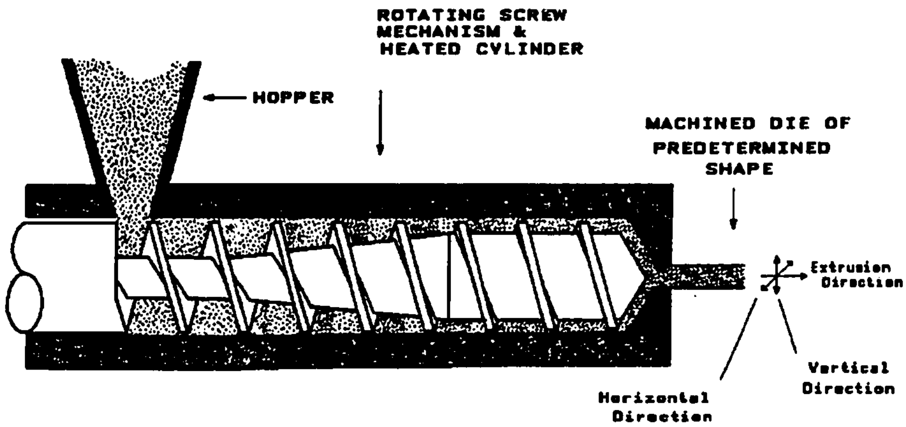


Figure 5. Extrusion process.

Impact Testing Procedures

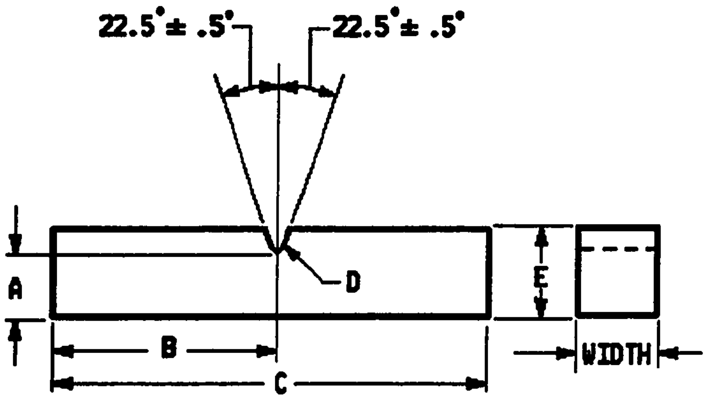
In performing the impact tests, test method A of the American Society for Testing and Materials (ASTM) Standard Test for Impact Resistance of Plastics (Designation D 256-90b) was used (ASTM, 1990; Prosen,1967; Rudd,1992). This test method employs a cantilever beam (Izod type).

Test specimens were modified to conform to the dimensions listed in section 6 of ASTM D 256-90b (see Figure

6). All samples were notched as per ASTM specifications in D 256-90b. Specimens were a maximum of 63.50 millimeters long and 12.70 millimeters wide. A notch consisting of a 45 degree angle, 0.25 millimeters deep, was located 32 millimeters from the end of the specimen. A minimum of five test specimens, from each composite board, and the nonreinforced plastic specimen, were used for the determination of impact values. Reporting standards for impact energy and type of failure as specified in D 256-90b were followed.

Pendulum impact energy was determined by measuring a test of the pendulum without a specimen in the vise. The readings of the test were considered frictional measurements and were subtracted from the test readings of the samples.

Impact test were done at three different temperatures: (a) ambient room temperature (23^0 C), (b) low temperature (-196^0 C), and (c) high temperature (60^0 C). For the two minute immersion in liquid nitrogen, a flask of liquid nitrogen was placed next to the impact testing machine. The test specimens were immersed for two minutes and then immediately picked and placed in the impact vise prior to testing. For the heated specimens, specimens were placed in a 60^0 C furnace for one hour and then removed and placed immediately in the impact vise prior of the application of the impact load. Test procedures utilized, calculations made and the report generated, where applicable, follow the guidelines and standards set by ASTM D 256-90b.



Dimensions (mm)

A 10.16 ± 0.05
B 32.00 max
31.50 min
C 63.50 max
60.30 min
D 0.25R ± 0.05
E 12.70 ± 0.15

Figure 6. Izod type test specimen.

The value of conducting notch impact tests is that this analysis yields information about the energy absorbing properties or toughness of the material under study. Toughness is an important engineering quality used in the design process. In many applications, impact resistance can actually be the primary criterion for design. Impact resistance can be defined as the relative resistance of a component to failure due to stresses applied at high rates (Trantina & Nimmer, 1994, p. 243).

The ability to absorb stress is temperature dependent in many materials. Smith (1993) asserts that conducting impact tests at different temperatures can be useful in defining the temperature range for the transition from ductile to brittle behavior. Although the effect of temperature on the impact properties is not found in the literature, Figure 7 shows the effect of temperature on the tensile strength of thermoplastics. It is obvious that as the temperature increase the weaker is the plastic. Smith (1993) indicates that this is due a weakening of the secondary bonding forces between the molecular chains caused by increased temperature. This pronounced decrease in tensile yield strength, due to a weakening of the secondary bonding forces, indicates that this thermoplastic material has been heated through its glass transition temperature T_g.

Understanding the possible effects of a sharp change in ductility and toughness of any material due the influence of a transition temperature is of critical importance in the materials design and application process. The use of multiple tests (notch impact, tensile, and flexure) was designed to provide the best possible range of data within the time, equipment and monetary constrains under which this study was conducted.

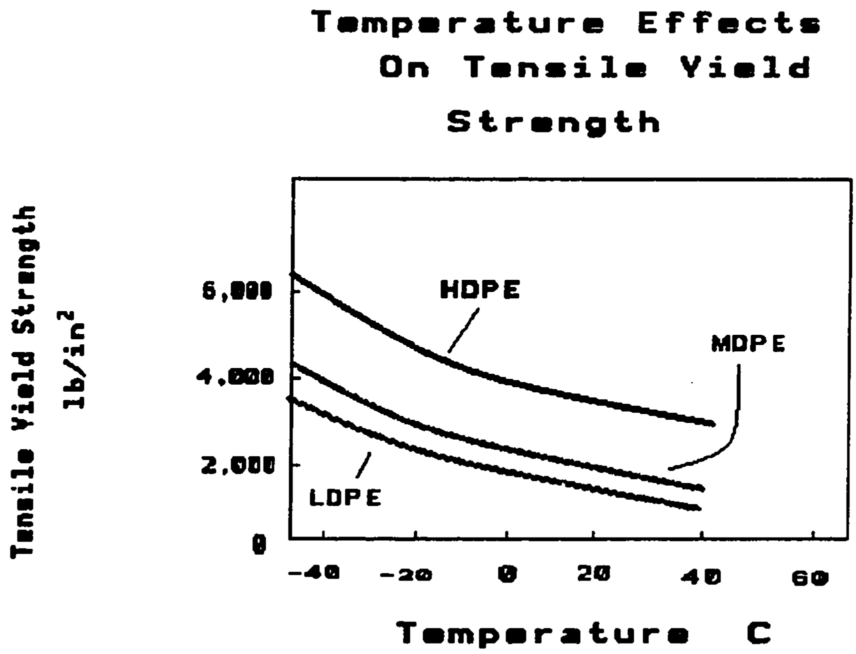


Figure 7. Effect of temperature on tensile yield strength.

Tensile Testing Procedures

In performing the tensile tests, The American Society for Testing and Materials (ASTM) Standard Test Methods for Tensile Properties of Plastics (Designation D 638-90) were used (ASTM, 1990). This test method has been designed to produce tensile properties data (i.e. tensile strength and % elongation) for control specimens and specification of plastic materials as well as composite materials, and their qualitative characterization.

Test specimens conform to the specifications listed for Type I tests (see Figure 8) except where noted. Type I tests are those that are applicable for reinforced composite materials. A minimum of five test specimens were prepared for each material that was being tested. Materials being tensile tested were 1 nonreinforced plastic 2 x 4, and 12 composite boards (with different fiber volume fraction percentages, different fiber lengths or different fiber reinforcement material).

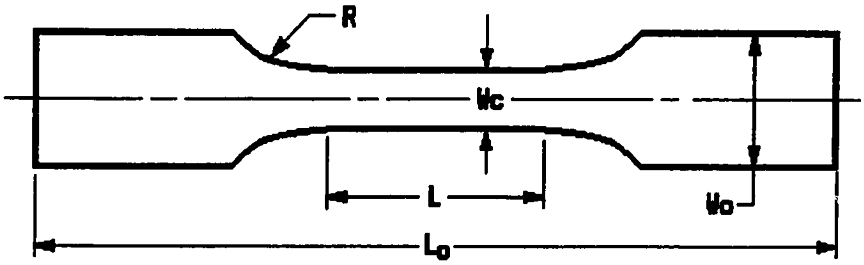
Tests were conducted Applied Test Systems Series 900 Universal Testing Machine. Crosshead travel speed was set at 250 millimeters/minute. Peak specimen load values were displayed for each test and utilized in the calculations made.

The nonhomogeneous nature of the test specimens (see Visual Examination of Specimens in Chapter 4) required that an alternative approach was used to test the lumber. Due to the heterogeneous nature of the lumber samples, ASTM standard test specimen size, and the size requirements of the Applied Systems Series 900 Universal Testing Machine, two tensile test groups were prepared for testing. To compensate for variations due to the heterogeneous nature off the test lumber, test groups were prepared with a 90^0 orientation difference in relation to the lumber centerline. Group 1 was oriented along the vertical direction of the specimen cross section and Group 2 was oriented on the horizontal direction of the specimen cross section. Moreover, differential density problems in the samples presented a great deal of difficulty in preparing test specimens according to ASTM guidelines. Group 1 samples (vertical direction specimens) were manufactured to ASTM standards but Group 2 (horizontal direction specimens) were not reduced in diameter as specified in the standard. This modification was required to achieve greater accuracy and more representative information about the material characteristics of the test lumber.

Tensile tests are the most commonly used method for determining the mechanical properties of any material such as strength, toughness, and ductility. The ASTM tensile testing process is one of the standard ways in which a material mechanical properties are defined and compared. Engineering stress-strain curves can be generated from the information obtained during a tensile test. This allows a materials user to contrast different material properties with some confidence that accurate comparisons can be made.

Tensile strength can also be an indication of the quality of the material under study. Porosity or inclusions in the test specimens may cause the tensile strength of those specimens to be lower than normal.

Test procedures utilized and report guidelines, where applicable, conform to the standards outlined in ASTM D 638-90. Calculations of fracture strength and percentage elongation also follow the guidelines set down in ASTM D 638-90 and were determined from the test information recorded on Applied Test Systems, Inc. ATS X-Y Recorder (Allen Datagraph 700 Series).



Specimen Dimensions (mm)
Type I Test

L - Length of narrow section	57 ± 0.5
Lo - Length overall min.	165 (no max)
Wo - Width overall min.	19 + 6.4
R - Radius of fillet	76 ± 1
Wc - Width of narrow section	13 ± 0.5

Figure 8. Tensile type test specimen.

Flexure Test Procedures

In performing the flexure tests, test method 1 of the American Society for Testing and Materials (ASTM) Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

(Designation D 790-90) were used (ASTM, 1990) was used. Test Method 1 designates a three point loading system where the test specimen was supported by two points with load imposed by means of a loading nose midway between the supports (see Figure 9).

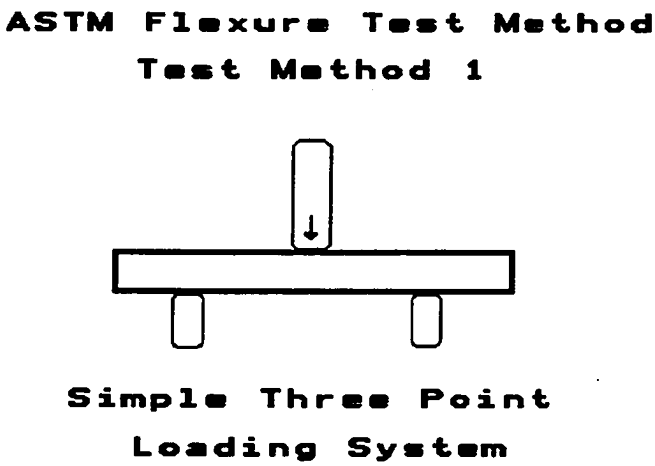


Figure 9. ASTM flexure test method 1.

Support span-to-depth ratios of the test specimens were calculated according to ASTM standards with a length to depth of 16 to 1. Distance between the load cell supports was 16 inches (40.6 centimeters). Test specimens were 50 centimeters (19.5 inches) in length, 3.81 centimeters (1.5 inches) in depth, and 8.89 centimeters (3.5 inches) wide.

Tests were conducted using an Applied Test Systems Series 900 universal testing machine with a crosshead travel rate of 250 millimeters/minute.

Test specimens required no special preparation except for cutting the boards to the required length. Limitations on the amount of available test lumber, of the required length, restricted the number of test samples to only thirteen tests. Test procedures utilized and report guidelines, where applicable, conform to the standards outlined in ASTM D 790-90.

The value of conducting flexure tests is that the data collected during these tests are often utilized in quality control and for design specification purposes. Harper (1992) indicates that many plastics do not exhibit equal tensile and compressive moduli. This indicates a possible variation in flexure strength due to an apparent thickness effect. ASTM guidelines on recommended span-to-depth ratios, maintenance of original dimensions, and test procedures were designed to compensate for this variation.

Statistical Analysis and Data Presentation

Due to the unavoidable problems involved in manufacturing and process control of composite materials, there exists the fact that the data collected from any test conducted on composite materials will have a greater degree of variability than that associated with other materials. This can lead to problems in interpretation and mistaken conclusions when applying this data to larger populations. Harper (1992) warns against the problem of over generalizing based on only a single mechanical property test. The methodology designed for this study based on this caution and employed three individual but related test procedures.

Data collected during this study was analyzed using an Analysis of Variance (ANOVA) tests at the 0.05 level of significance. Standard statistical procedures were applied to the data to ascertain if unexpected manufacturing and process variability is present (Witte, 1989). Based on preliminary information, seven hypothesis were generated. Each of the proposed hypothesis was subjected to hypothesis testing. To aid in this process, statistical analysis of the collected data was accomplished using a commercially available computer statistics package (CRUNCH4) manufactured by Crunch Software Corporation of Oakland, California.

CHAPTER 4

RESULTS AND DISCUSSION

The data collected from 193 notched impact tests, 106 tensile tests and 13 flexure tests are presented and analyzed in this chapter. All collected data were analyzed using Analysis of Variance (ANOVA) tests at the 0.05 level of significance with all factor combinations of means (Evered & Miller, 1991; Witte, 1989). All data sets were also tested for homogeneity within cell variances by the Bartlett Test of Homogeneity.

Data tables were constructed for mean experimental values for individual variables and all possible combinations of the treatment effects. The dependent variable for the notch impact and the flexure tests were maximum fracture load. Dependent variables for the tensile tests were maximum fracture load and elongation. Elongation percentages figures were also calculated.

Additionally, tables were constructed for all tests which listed the individual and combined treatment effect, the degrees of freedom *df*, the unique sums of squares SS(U), the mean sums of squares MSS, the f ratio *F*, and the p-value *p*.

Visual Examination of Specimens

Visual examination of the composite plastic materials being tested revealed some interesting information. External examination of the composite 2 x 4s , actual dimensions were 3.81 cm thick by 8.89 cm wide by 188 cm long, under study revealed sections at the beginning and end of some of the lumber boards which were not uniform in size or appearance when compared to the rest of the sample. These surface defects were caused by lack of sufficient plastic resin at the beginning and end of the extruded process. No test samples were selected or used from these sections.

Moreover, visual examination of the composite lumber revealed a variation in the width of the lumber due to shrinkage. Apparently, this was due to post manufacturing shrinkage as the plastic fiber matrix cooled. As all test specimens were prepared according to ASTM standards and were manufactured to specific dimensions, this shrinkage problem was not a difficulty in this study. Only the flexure tests were conducted with 'as manufactured' specimens.

Internal examination of the composite 2 x 4s revealed distinct areas of inconsistency in the structure of the test specimens. In all specimens, there existed two distinct microstructures in the material. An inner core of approximately 1.7 centimeters in diameter contained a zone of apparently less dense material. This area was completely surrounded by two layers of denser plastic and/or plastic fiber mixture of approximately 2.1 centimeters (see Figure 10 and Figure 11).

The heterogenous nature of the samples can be attributed to the pressure distribution exerted during the extrusion process on the specimen. The extrusion process is a complex involving three distinct machine sections: (a) a feed section; (b) a transition section; and (c) a pumping section. Melting occurs in the transition section of the extruder. Additional melting takes place in the pumping section and at a pressure buildup at the die.

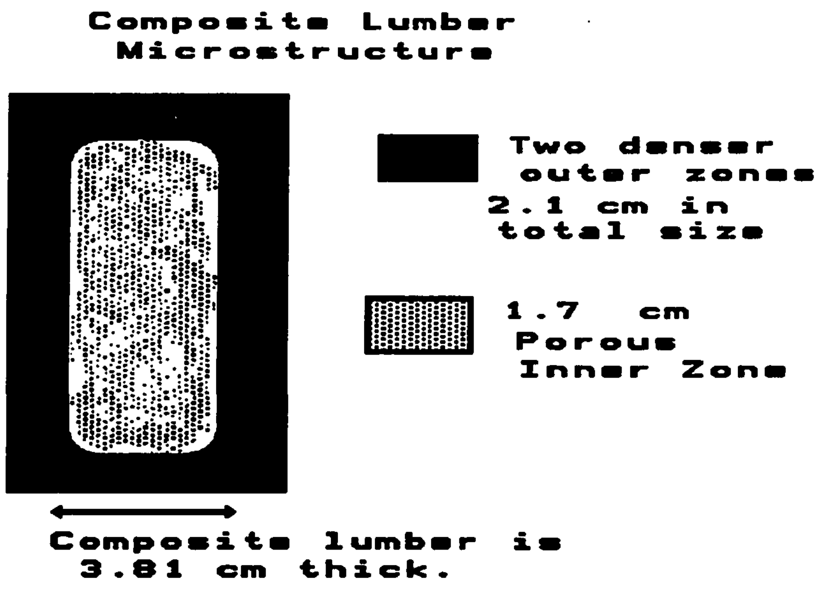


Figure 10. Composite lumber microstructure.

Goetsch (1991) identifies this area as a metering zone where plastic and reinforcement fibers are conveyed to the die at uniform rates and high pressure (p. 92). This compression of material through the die is what produces the desired shapes. The proper compression ratio for the product being manufactured is dependent upon the material used, the different material densities, and bulk densities.

The author believes that because the specimens being manufactured were prototypes, there existed no information on which to make manufacturing decisions such as compression ratios. Therefore, an inaccurate compression ratio was used during the extrusion process for the size and part geometry of the test lumber, which resulted in a lower extrusion pressure than was needed. This lower pressure resulted in the heterogeneous microstructure observed in the test specimens.

The heterogeneous nature of the test specimens presented difficulties in the preparation of test samples. ASTM requirements called for standard test samples to be of specific size (see Figures 6 & 8). Tensile specimens could not be produced without containing portions of both the outer dense material and the inner porous zone.

To compensate for the heterogeneous nature of the lumber, and the effect it might have on the data collected, an additional set of tensile tests (called Group 2) were

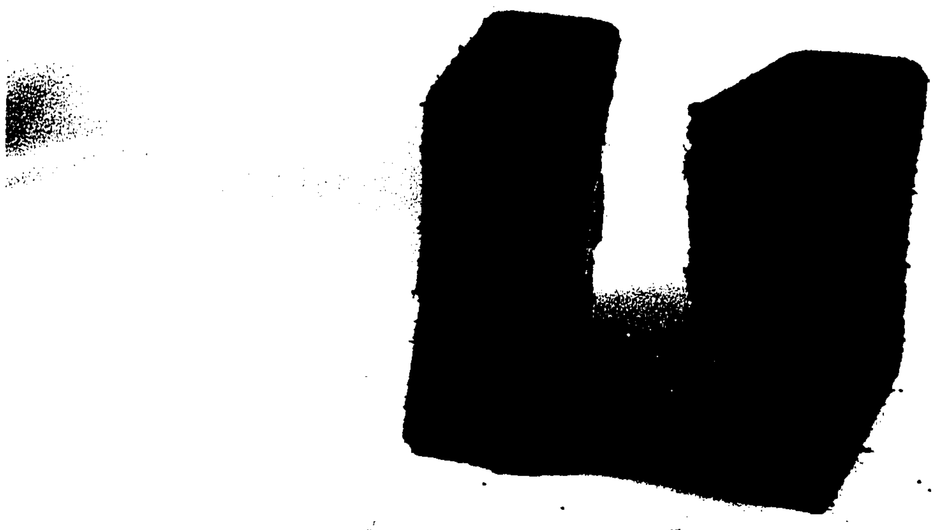


Figure 11. Picture of composite lumber microstructures.

performed. These specimens were prepared by taking samples from the lumber with a 90^0 longitudinal orientation shift in the horizontal direction relative to extrusion, when compared to the original samples, to provide more complete data on the mechanical properties of the lumber.

Additionally, flexure tests, not originally contemplated in the experimental design, were performed to obtain corroborative data about the properties of 'as manufactured' test samples.

ASTM size requirements for the notch impact test samples allowed samples to be prepared which did not include portions of both zones. Because samples were prepared from all sections of the test lumber, a mean value for all notch impact samples tested will be representative of the entire microstructure under study.

Impact Tests

The data presentation and analyses for the 193 individual notch impact tests, grouped in four individual and 15 combined treatment groups, are found in Tables 2-10 located in Appendix B: Impact Test ANOVA Tables. The tabular data presented includes: (a) the variable being tested with the letter F designating fiber type, L representing fiber length in cm, P representing fiber volume fraction percentage and T representing temperature in degrees celsius, (b) the number _n_ of individual tests which are used in this population, (c) a mean impact energy _M_ necessary to break the test specimens expressed in joules per second, and (d) a standard deviation value _SD_.

The data presented in Tables 4 through 10 was rank ordered for easier comparison with appropriate notation. Tests were conducted at temperatures of - 196^0, 23^0, and 60^0 Centigrade; on a control sample that had no fiber reinforcement (100% Plastic) indicated by label C, soybean stalk fiber labeled S or oatstraw fiber designated O; with fiber lengths of approximately 0.00 (no fiber added), 0.64, 1.91, and 3.81 centimeters in length; and fiber volume fraction percentages of approximately 0, 25, and 30%.

Independent variables being monitored during these impact tests were the effects of temperature, fiber type, fiber length, and fiber volume fraction percentage. The dependent variable was notch impact fracture energy.

The Effects of Temperature

As illustrated in Figure 12, the effects of temperature variation on the notch impact strength of the test specimens was different than expected. The mean notch fracture loads of the three temperatures tested were 9. 88 Joules/second (J/S) for 23^0 C, 8.79 J/S for 60^0 C and 3.2 J/S for - 196^0 C.

The review of the literature indicates that, at least for certain engineering materials, a change in the capacity to absorb energy or toughness is temperature dependent. The effect on thermoplastics, of increased temperature, can be a decrease in mechanical strength due to a decrease in secondary bonding forces between the molecular chains. The data illustrated in Figure 12 indicates that the notch impact test specimens exhibited characteristics which suggest that a decrease in bonding forces did occur. Maximum toughness occurred in the specimens that were tested at ambient room temperature (23^0 C). An increase in test temperature resulted in a 11% decrease in measured energy resulted when the samples were tested at 60^0 C.

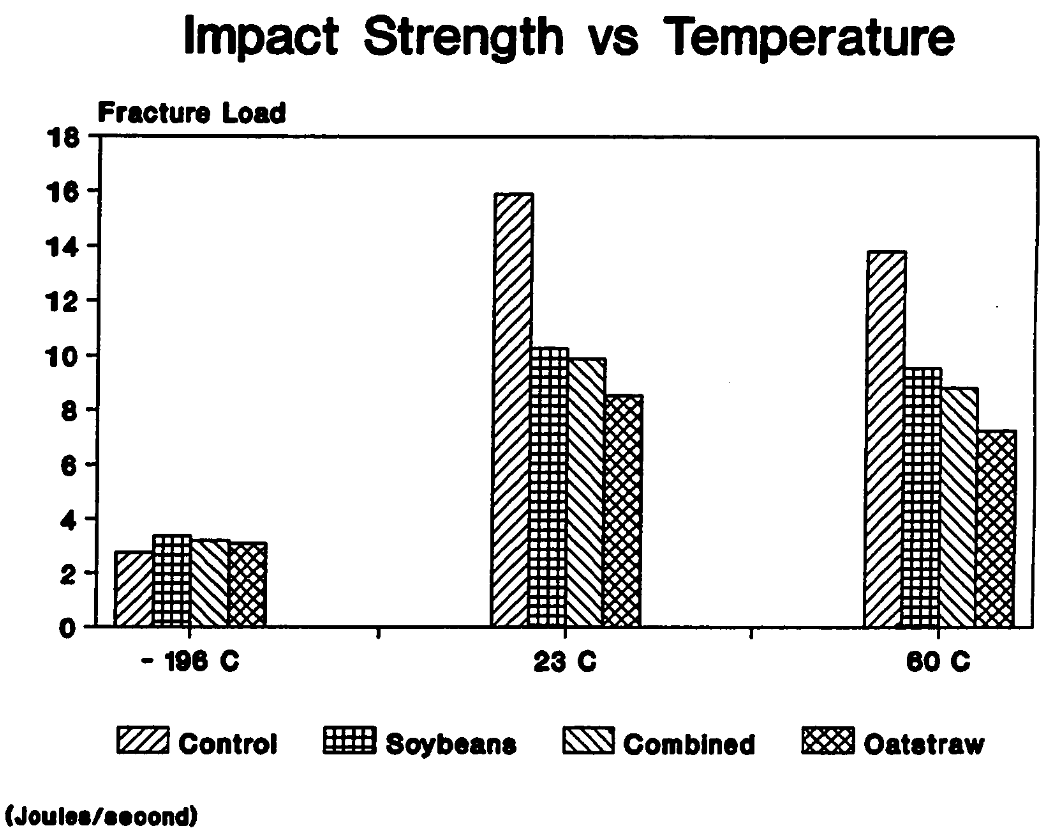


Figure 12. Impact strength vs temperature.

Samples tested at - 196^0 C were expected to show a dramatic decrease in impact fracture energy due to the brittle nature of plastics at extremely low operating temperatures. Preliminary test data, as well as the literature, indicated that all samples should have decreased performance at colder temperatures (Smith, 1993). As expected, the mean impact fracture energy required to break the test specimens at the colder temperature was less than that necessary at 23^0 C (68% less).

The data presented in Figure 12, for each individual fiber type and a combined sample (for the case where fiber types are mixed), indicated that there appears to be only a slight decrease in impact fracture strength between test taken at 23^0 C and those taken at 60^0 C. On average, the decrease in fracture load required at 60^0 C was only about 1.3 to 2 J/S. However, there appears to be a dramatic decrease in impact fracture strength due to a decreased temperature when data at - 196^0 C was compared to that of 23^0 C. Average decreases in fracture strength for this group of readings was in the range of 6 to 13 J/S. Analysis of the data presented in Tables 4 and 6, located in the Appendix, indicated that tests in colder temperatures always had the lowest performance readings regardless of reinforcement material, fiber percentage, or fiber length.

Statistical analysis of the information, presented in Table 3, indicated that the critical $\underline{F}$ ratio value for temperature is 1.361 and the $\underline{p}$-value reading is 0.2591. All test samples met the criterion for the Bartlett test for homogeneity. These statistical values support the acceptance of the null hypothesis H_{03} and the rejection of hypothesis H_3. This would indicate that comparisons between the temperature of the test specimens, while appearing to have a significant effect on fracture strength, did not show any significant statistical difference in the mean impact values.

The Effects of Different Fiber Types and Fiber Volume Fraction Percentages

The number of possible reinforcement materials useful in the manufacture of composite materials is nearly unlimited. Some reinforcement materials undoubtedly will be superior in performance to others. The concept that differences in material performance that can be attributable to different fiber types is validated by this study.

Of the two agricultural fibers under study, the data indicates (as presented in Figure 13 and Tables 3 and 5) that significant performance differences occurred due only to the different reinforcement materials. The addition of any reinforcement fiber to the plastic matrix resulted in a deterioration in impact performance. Adding soybean stalks as reinforcement material resulted in an average decrease in energy needed to fracture the sample from 10.81 J/S to 7.72 J/S. This 29% decrease was, however, better than the performance of the oatstraw fibers. A decrease in fracture energy from 10.81 to 6.34 J/S (41%) occurred when oatstraw was the selected reinforcement material. Clearly, the best of the reinforcement materials was no reinforcement fiber.

This unexpected finding can possibly be explained by the manufacturing difficulties already mentioned. The function of the reinforcement material is to provide a stronger medium to bear the imposed load rather than the

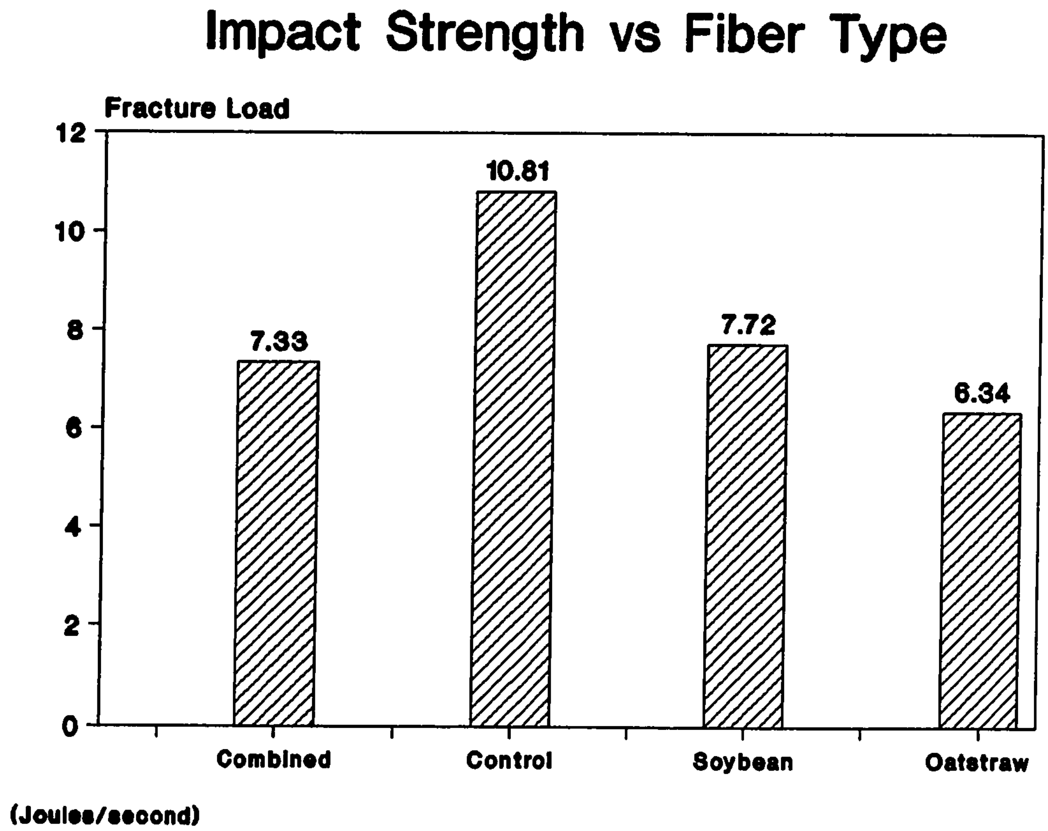


Figure 13. Impact strength vs fiber type (all factors).

weaker plastic. The interaction or connections between the fiber and the matrix is therefore critical. The process of manufacturing and testing a prototype material is a learning process. Incorrect assumptions, inaccurate manufacturing procedures, and hidden process variability are often common problems that are encountered. The author believes that the manufacturing techniques used for this product resulted in a heterogeneous product. The duality of the microstructure prevented the expected performance enhancement of the matrix by the reinforcement fibers. These fibers, rather than adding strength to the matrix, instead acted as crack initiators and decreased the impact, tensile and flexure strength of the material under study.

This theory is corroborated by the data gathered about fiber volume fraction percentage (see Figure 14). Preliminary test data indicated that oatstraw reinforcement material was more effective at the higher fiber volume fraction percentages. Tests conducted at 23^0, 60^0 and -196^0 centigrade produced higher fracture loads at the upper fiber volume fraction percentages. For soybean stalk reinforcement material, the trend is comparable except for the tests conducted at elevated temperatures (49^0 C) where better performance was achieved at the lower percentages.

Notch impact tests conducted for this study demonstrated that the best impact performance was achieved by the test samples which were not reinforced. On average, those test samples required 10.81 J/S of energy to fracture. The next best performance level was demonstrated by samples reinforced with 25% fiber reinforcement (7.29 J/S) and the worst performance record was 30% fiber reinforcement (6.79 J/S). This is so clearly different from results achieved in the preliminary tests that the author believes that other factors must be responsible for it. The influence of carbon black added to the matrix as a ultraviolet shield, process interactions due to part

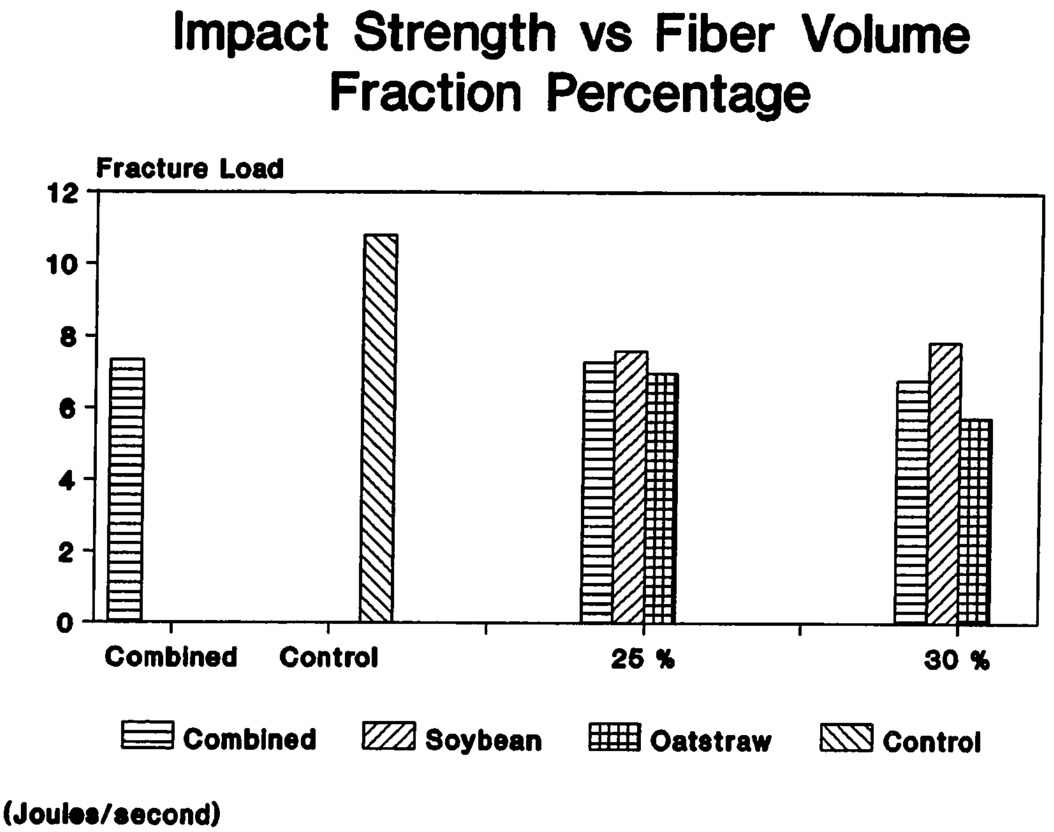


Figure 14. Impact strength vs fiber volume fraction percentage.

geometry and part size, and hidden process variables (i.e. pressure, temperature, and compression ratios) might be responsible for the results obtained.

Moreover, statistical data presented in Table 3 supported the conclusion that both hypothesis H_1 and H_2 should be accepted as accurate statements. Both treatment effects (different fiber types and volume fraction percentages) have p value readings of 0.0000 and F ratio values of over 26.9 (26.915 for fiber type and 26.995 for fiber percentage). The statistical analysis of this data reveals that fiber type and fiber fraction volume percentage have a very strong effect or influence on the impact strength of the test specimens.

The Effects of Fiber Length

Analysis of the data concerning optimum fiber length presented findings that were at odds with the literature reviewed for this study. The literature indicates that among the reinforcement processes, continuous oriented fiber reinforcement was preferred. Among the randomly oriented reinforcement practices, the longer the reinforcement fiber the better the mechanical performance has been (Gibson, 1994; Naitove, 1987; Peters, 1992).

Data collected during this study and presented in Figure 15 and the tables in Appendix B, indicated that the best performance was obtained by no fiber reinforcement material (see Figure 15). The longer the fiber reinforcement material used, the worse the impact performance became for oatstraw.

The author believes that the microstructure coring problems described in this chapter, along with manufacturing variables such as the effect of part geometry and part size on fiber orientation are responsible for this effect on the test data. These factors, when compared to industrial experiences and the reviewed literature, strongly suggest the need for reformulation and adjustment of the manufacturing protocols for the composite material under consideration.

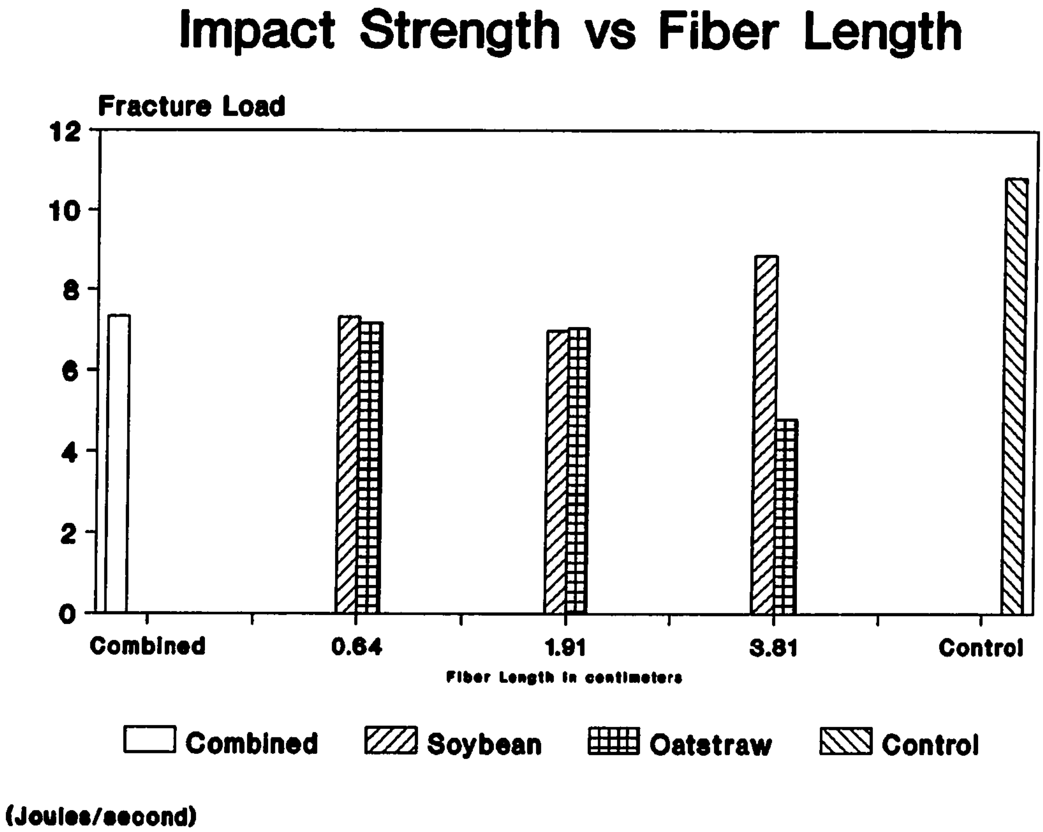


Figure 15. Impact strength vs fiber length.

This conclusion was also supported by the statistical analysis, presented in Table 3. That analysis indicated that fiber length was a significantly important treatment variable. The statistical analysis determined that differences between impact strength due to the fiber length differences within the sample population had a p value of 0.0000 and a F ratio reading of 16.364. Both of these statistical parameters would support a rejection of the null hypothesis H_{06} and the acceptance of hypothesis H_6 that fiber length was responsible for a significant difference in the mean impact values of the test samples.

Tensile Tests

The data presentation and analyses for the 106 individual tensile experiments, grouped in three individual and seven combined treatment groups are found in the tables located in Appendix C: Tensile Test ANOVA Tables (Group 1) and Appendix D: Tensile Test ANOVA Tables (Group 2). Group 1 test specimens were prepared with a vertical cross section direction orientation. Group 2 test samples had a horizontal cross section orientation. The tabular data presented includes: (a) the variable being tested with the letter F designating fiber type, L representing fiber length, and P representing fiber volume fraction percentage, (b) the number n of individual tests which are used in this population, (c) a mean fracture energy M necessary to break the test specimens expressed in newtons and the maximum distance the test sample elongated under load measured in centimeters, and (d) a standard deviation value SD.

The data presented in Tables 13 through 16 will be rank ordered for easier comparison with appropriate notation. Tests were conducted on a control sample that had no fiber reinforcement (100% Plastic) labeled C, soybean stalk fiber labeled S or oatstraw fiber designated O; with fiber lengths of approximately 0.00 (no fiber added), 0.64, 1.91, and 3.81 centimeters in length; and fiber volume fraction percentages of approximately 0, 25, and 30%.

Independent variables being monitored during these tensile tests were fiber type, fiber length and fiber volume fraction percentage. Dependent variables were maximum fracture load and maximum test specimen elongation.

The Effect of Fiber Type

The primary function of many building materials is to bear loads (either in tension or compression). The ability of composite materials to do this is dependent, to a large extent, on the fiber reinforcement material used in the matrix. Different fibers have varying performance levels. Of the two different fibers under study, the data indicates (as presented in Figure 16 and 17, Tables 11 and 13 through 15, and Tables 17 and 19 through 21) that significant differences occurred in the tensile strength of the test samples due to different reinforcement materials. As with the impact test data, the tensile tests revealed that the use of any of the reinforcement materials under study decreased tensile fracture load strength as compared to the control (no fiber) group.

Of the two sample groups tested, both groups performed nearly alike in regard to different fiber types (see Figures

16 and 17). While fiber orientation was an important factor, as shown by the increase in fracture strength of Group 2 samples, the relative test results, on fiber type, did not vary. Both test groups revealed that the highest

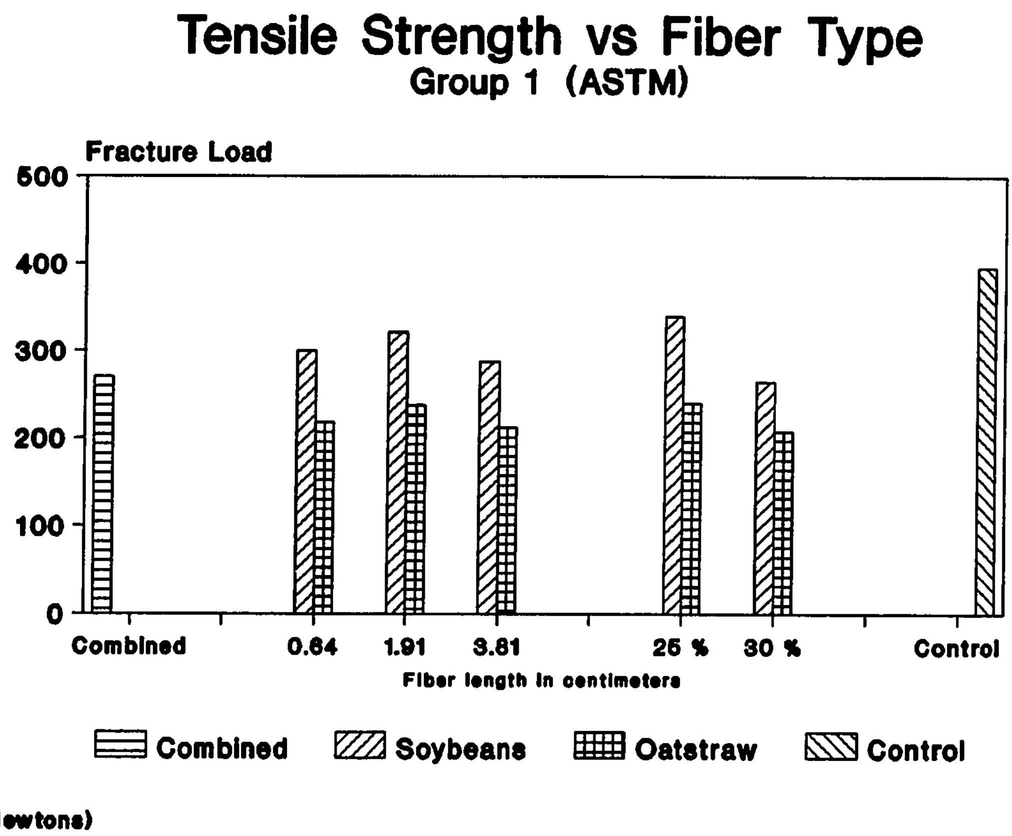


Figure 16. Group 1 tensile strength vs fiber type.

tensile fracture load was achieved by the control sample which had no reinforcement fibers (396.59 newtons for Group 1 and 881.12 newtons for Group 2). On average, soybean fibers were the best performing of the reinforcement material with peak readings of (301.94 and 627.91 newtons respectively). In both test groups, oatstraw reinforced specimens tested, on average, the lowest in fracture strength at 222.52 and 479.39 newtons respectively.

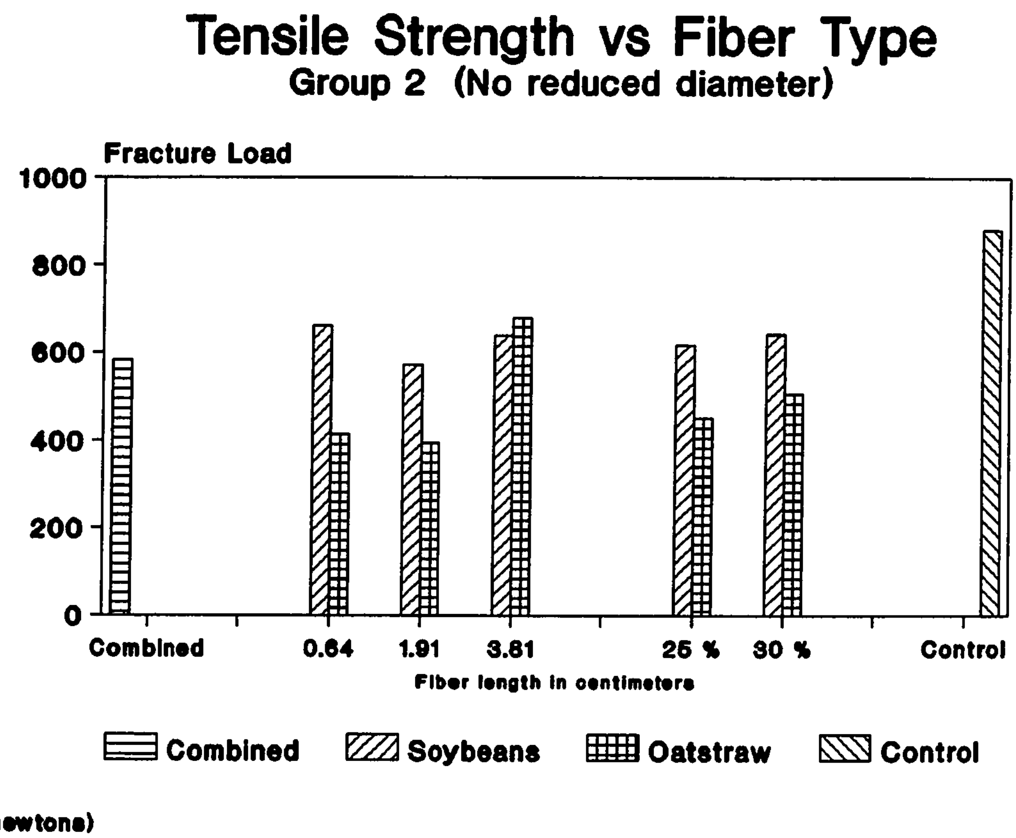


Figure 17. Group 2 tensile strength vs fiber type.

Comparing the mean experimental tensile fracture loads of each group to the control sample revealed some interesting similarities. In both test groups, the decreases in average performance, between the samples, were similar. The soybean specimens had a 24-28% decrease in strength when compared to the control sample. The oatstraw samples decreased 44-46% in performance when compared to the control sample. This would suggest that the influence of different fiber types outweighs that of fiber orientation.

As a measure of ductility, comparing data on the mean elongation percentages of the different test groups, Figure 18 and 19, revealed some interesting parallels. The different orientations of the test specimens, within the larger specimen, resulted in only a 1-1.5% elongation difference between the groups. In both test groups, the difference in elongation percentage due to different fiber types was small. Both fiber types performed nearly identical in this regard. The difference in elongation percentages, when comparing soybean stalks and oatstraw, was only 0.2-0.3%. This would indicate that while there are differences in tensile strength between fiber types, there was no performance difference in regard to elongation.

The concept that different fiber types were a significant variable in the fracture load tensile tests was supported by the statistical analysis presented in Tables 12 and 18 located in Appendix C and D. The data for fracture load revealed that fiber type had a $\underline{p}$ value reading

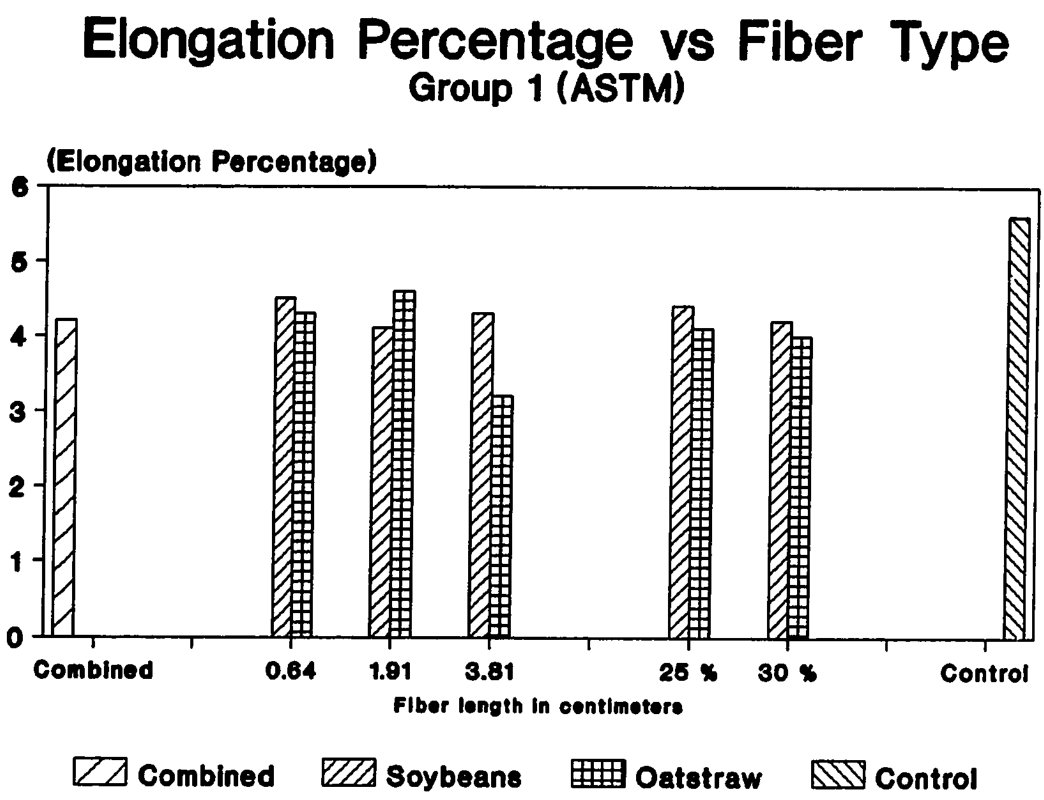


Figure 18. Group 1 elongation percentage vs fiber type.

of 0.0000 and a F ratio value of 11.917 for Group 1 vertically oriented cross sections. The statistical analysis of Group 2, or horizontally oriented test sample cross sections, revealed a p value reading of 0.0007 and a F ratio value of 10.489. No other individual or combined treatment variable (for fracture load), for either test group, was this high. This information would support the conclusion that hypothesis H_4 should be accepted and that null hypothesis H_{04} should be strongly rejected. This would

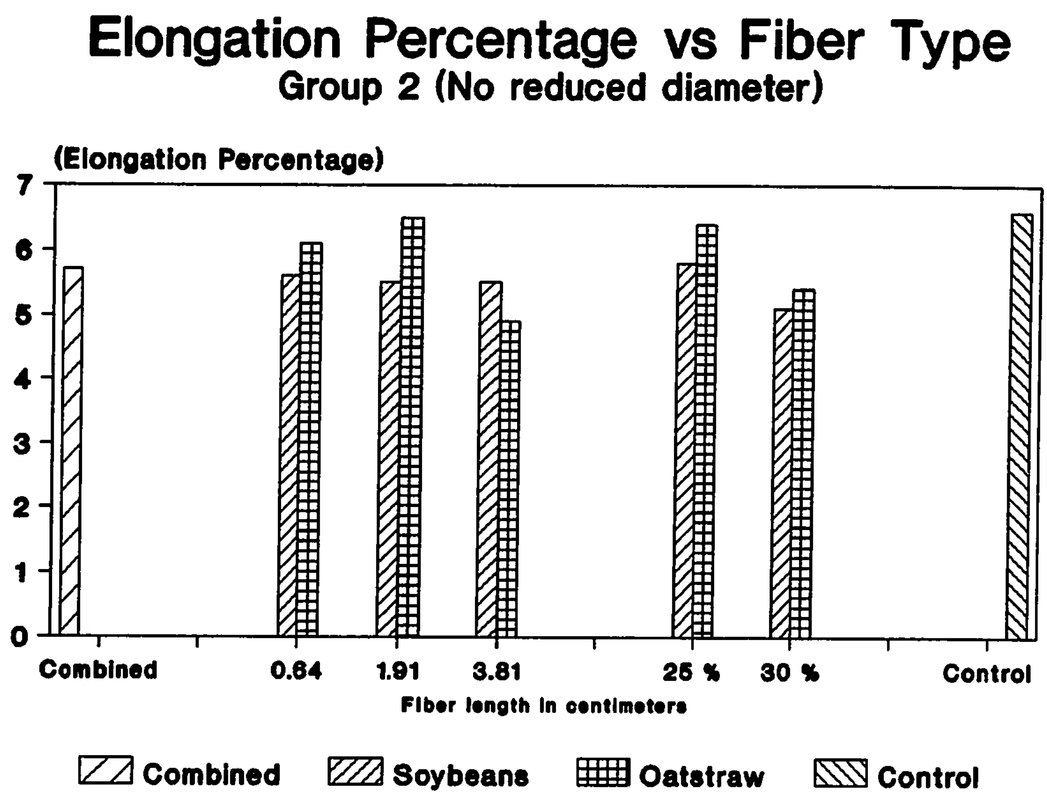


Figure 19. Group 2 elongation percentage vs fiber type.

indicate that there was a significant difference in tensile strength attributable to fiber type.

For the effect of fiber type on elongation percentage, the statistical analysis for Group 1 indicated that all three individual treatment variables (fiber type, fiber length and fiber volume fraction percentage) were significant. Fiber type had a p value reading of 0.0000 and a F ratio value of 12.005. Fiber length had a p value reading of 0.0000 and a _F_ ratio value of 13.381. Fiber volume fraction percentage had a _p_ value reading of 0.0000 and a _F_ ratio value of 11.243. This data supports the idea that, in regard to elongation percentage, all three individual variables (fiber type, volume fraction percentage, and fiber length) in Group 1 were significant and have equal impact on the ductility of the composite. This information would also support the conclusion that hypothesis H_4 (that fiber type is significant) should be accepted and the null hypothesis H_{04} should be strongly rejected.

However, the statistical analysis for the Group 2 (horizontally oriented samples) tensile tests indicates that these individual and combined treatment effects were not significant. _P_ value readings from 0.8985 to 0.0545 and _F_ ratio values ranging from 2.712 to 0.296 indicate that there was a very significant difference between the performance of the test groups in regard to elongation percentage. The author believes that these differences can be explained by the variables in the manufacturing process already mentioned and the hidden effects of the prototype part geometry and size.

One of the process variables which was not controllable was fiber reinforcement orientation. During the manufacturing process, no conscious attempt was made to influence the orientation of the reinforcement fibers. The extrusion process and the relative size of the 3.81 centimeter reinforcement fiber, when compared to the overall part size, resulted in a natural alignment of the fiber along the longitudinal axis of the lumber boards. This preferred orientation, I believe, was the reason for the significant differences in elongation performance between the two test groups. This theory could explain the differences that occurred in the test data between the two test groups. This is also a factor in the different test results obtained when analyzing tensile strength and elongation percentage due to the effect of fiber length.

The Effect of Fiber Length

The effects of fiber length presented some of the most interesting data collected during this study. As mentioned earlier in this chapter, two sample test groups were used in the tensile tests because of the possible differences in material performance due to the microstructure coring problems previously mentioned. The importance of fiber orientation was noted in the literature review but no effort was attempted to control this variable.

The heterogenous nature of the test samples suggested that the specimens could have been anisotropic properties. This would mean that the test specimens might have different mechanical characteristics dependent on testing orientation. Samples were prepared that had different orientations, relative to the original test sample, so that a more representative and comprehensive portrait of the test specimens mechanical properties would emerge.

Up until this point, analysis of the test data has shown that the test material has performed nearly identically in all respects (except for elongation percentage). This indicates that the effects of fiber type has been consistent regardless of fiber orientation. Analysis of the effects of fiber length on tensile strength did not follow this trend. As shown in Figure 16 and 17, there is a difference between the test groups in the mean experimental values of the different fiber lengths.

As previously mentioned, the author believes that this difference is due to the preferred orientation of the longer reinforcement fibers due in part to geometry, part size, and the extrusion process. In the tensile tests conducted on Group 1 specimens, the sample with no fiber reinforcement had the best performance of all test samples (see Figure 16). Group 2 tensile test samples performed in an identical manner in this regard. Clearly, the introduction of fiber reinforcement material degraded the tensile strength of the samples. This is consistent with the data collected on the impact and flexure tests.

The findings of this study on the effect of fiber length, excluding the control sample, showed significant differences between the test groups. In the Group 1 tests, the 1.91 centimeter fiber had a tensile fracture load strength of 277.71 newtons (N), followed by 0.64 cm fiber (257.66 N), and 3.81 cm fiber (251.65 N). Group 2 fiber length performance followed the opposite rank order. The tensile strength of the Group 2 fiber samples was in the following order: 3.81 cm (655.98 N), 0.64 cm (537.57 N), and 1.91 cm (469.69 N). Additionally, the greater range of the mean tensile fracture strength values of Group 2 compared to Group 1 specimens was an indication that the different fiber orientation of the samples was important.

One possible explanation of this tendency was that the different fiber lengths interacted with operating variables of the extrusion process to produce a higher friction coefficient. Factors affecting the coefficient of friction of the reinforcement material during the extrusion process would be (a) length, (b) fiber type, and (c) volume fraction percentage. The different friction coefficients could effect a change in the viscosity of the matrix material resulting in variations in homogeneity of the finished product.

The analysis of the elongation percentages of the different test group specimens demonstrated that fiber length had minimal effect on the elongation of the test samples. Expecting dissimilar test results like those for fracture load, the elongation percentages analysis revealed identical findings. Except for a 1.5% shift in the average elongation percentages (see Figure 19), the different fiber lengths performed identically. As expected, the sample with no fiber reinforcement had the largest percentage elongation. The samples with no fiber reinforcers had a mean elongation of 5.6% for Group 1 and 6.6% for Group 2. Fiber reinforcement lengths of 0.64 and 1.91 cm had nearly identical performance figures. These fiber reinforcement lengths had a 4.3% elongation percentage for Group 1 tests and a 5.9 to 5.7% elongation percentages for Group 2 tests. In both test groups, the longest reinforcement fiber (3.81 cm) had the lowest elongation percentages (3.7 and 5.2%). This would suggest that, as the literature review suggested, if fiber reinforcement is a treatment variable, the best performance is obtained by using the longest possible fiber reinforcement consistent with manufacturing capabilities.

The statistical analysis presented in Tables 12 and 18 located in Appendix C and D, indicates the influence that the different sample orientations had on the test results. In samples tested in the first group, the fiber length treatment (fracture load) had a p value reading of 0.0311 and a F ratio reading of 3.072. These readings were significantly different for the effect this treatment had on elongation. Fiber length treatment had a p value reading of 0.0000 and a F ratio value of 13.381. This would suggest that for the first group of tensile samples, fiber length was a very significant factor in regard to elongation but of lesser significance in fracture load.

The statistical analysis of the specimens in the second test group (samples with a horizontal cross section orientation) indicated different findings. The fiber length treatment, in regard to fracture load, had a p value reading of 0.0024 and a F ratio value of 6.807. The statistical values for the elongation effect show significantly different readings. The fiber length treatment had a p value reading of 0.3457 and a F ratio value of 1.171. This would suggest that fiber length was a significant variable in regard to fracture load but was not significant in regard to elongation.

The Effect of Fiber Percentage

The data has indicated that the change in tensile test sample orientation, from a vertical cross section direction for group 1 to a horizontal cross section orientation for group 2, has been seen to have a noticeable impact on the mechanical properties of the composite material under study. Nowhere was this more evident than in the analysis of the effect of different reinforcement fiber percentages.

The influence of different fiber volume fraction percentages did not modify the fact that the best impact fracture strength was obtained in the test samples with no reinforcement material (see Figure 16 and 17). Analyzing the impact of different fiber percentages for the individual test groups or overall proved to be very difficult. The variability of the test samples makes any generalized conclusions impractical.

The data revealed that each tensile test group had results which contradicted the other groups findings. In test Group 1 (vertical orientation), the overall findings indicated that 25% fiber reinforcement had a slightly higher mean tensile strength than 30% fiber reinforcement (293.36 N to 234.64 N). Information from the Group 2 tests (horizontal orientation) came to the opposite conclusion. Group 2 findings indicated that 30% fiber reinforcement was slightly better than 25% (566.53 N to 540.73 N).

Individual treatment combinations of specific fiber type and fiber percentages or specific fiber lengths and fiber percentages show the same variability. Test group 1 data, see Table 13 in Appendix C, indicates that the best combination of fiber type and percentage was soybean stalk fiber at the 25% reinforcement level (339.53 N). This was followed by soybean fiber at 30%, oatstraw at 25% and oatstraw reinforcement at 30%. Analysis of fiber length and fiber percentages indicated that the lower fiber reinforcement percentage (25%) coupled with the longer fiber lengths was the best combination.

Analysis of the data of the second tensile test revealed a different picture. The data from the tests in group 2 revealed that the optimum fiber type and percentage combination was soybean stalk fiber at the 30 percent level.

This was followed by soybean fiber at 25%, oatstraw at 30%, and finally oatstraw at the 25% reinforcement percentage. Analysis of different fiber lengths and fiber reinforcement percentages indicate that longest fibers and the highest reinforcement percentages was the best combination (see Table 19 in Appendix D).

Statistical analysis of the data presented in Tables 12 and 18 indicated contradictory findings in regard to the significance of different fiber percentages. Data for the Group 1 tensile tests indicated that different fiber percentages was a significant factor for fracture load. The statistical analysis revealed that fiber volume fraction percentage had a $\underline{p}$ value reading of 0.0005 and a $\underline{F}$ ratio value of 8.107. This would suggest that null hypothesis H_{05} (indicating that volume fraction percentage as a treatment was not significant) should be rejected and hypothesis H_5 (that volume fraction percentage was significant) be accepted.

Analysis of the statistical data presented in Table 18 contradicts this conclusion. The statistical analysis for the second tensile test group indicated that it was not a significant factor. In the group 2 statistical analysis, fiber volume fraction percentage had a $\underline{p}$ value reading of 0.3425 and a $\underline{F}$ ratio value of 1.152. These figures suggest that, in group 2, fiber volume fraction percentage was not a very significant variable. High $\underline{p}$ value readings and low $\underline{F}$

ratio readings indicate a high probability that the null hypothesis should be accepted.

Analysis of the effect of different fiber volume fraction percentages in regard to test sample elongation corroborated the data concerning that of fracture load. As expected, test sample elongation percentages indicated that the more fiber used as a reinforcement material, the less the test sample elongated. In all cases, the largest specimen elongation was experienced by the samples with no reinforcement material (see Figure 18 and 19). As expected, test samples which contained higher fiber reinforcement percentages elongated the least.

Analysis of the statistical data on fiber volume fraction percentage effects of part elongation revealed that the same findings as fracture load. For tensile group 1 test specimens (vertical orientation), different fiber volume fraction percentages was a significant factor on part elongation. The statistical data indicated a $\underline{p}$ value reading of 0.0000 and a $\underline{F}$ ratio value of 11.243. This would suggest that the null hypothesis H_{05} (that volume fraction percentage differences are not significant) should be rejected.

However, the statistical data for the second group of tensile tests contradicts this conclusion. That statistical analysis indicated that different fiber volume fraction percentages was not a significant factor. The statistical analysis indicated that fiber volume fraction percentage had a *p* value reading of 0.7478 and a *F* ratio value of 0.296. This would indicate that variation in the data collected was due to internal variation of the sample groups and that no external factors were acting on the samples.

The author believes that these differences are attributable to the impact of the microstructure coring problems discussed in this chapter and influence of preferred fiber orientation on the test samples. The contradictory nature of this data requires that further testing be conducted before the effect of this variable can be known. The acceptance or rejection of hypothesis H_5 (the significance of volume fraction percentages) or null hypothesis H_{05} (that volume fraction percentages are not significant) can not be supported by the data, at this time.

Flexure Tests

The heterogenous nature of the test specimens, due to microstructure coring problems, presented certain difficulties in obtaining information about the 'as manufactured' composite structure under investigation. ASTM test procedures and equipment limitations required sections of the test samples be analyzed rather than the complete structure in impact and tensile testing. Flexure tests on the test specimens provided an important source of information on 'as manufactured' test samples.

The data presentation and analyses for the 13 individual flexure tests, grouped in three individual and seven combined treatment groups, are found in Tables 23 and 24 located in Appendix E: Flexure Test ANOVA Tables. The tabular data presented includes (a) the variable being tested with the letter F designating fiber type, L representing fiber length, and P representing fiber volume fraction percentage, (b) the number *n* of individual tests which are used in this population, (c) a mean flexure load *M* necessary to fracture the test specimens expressed in newtons, and (d) a standard deviation value *SD*.

The Effect of Fiber Type

The clearest sign that different fiber reinforcement materials have a significant impact on flexural strength would be a large difference in the experimental values recorded during the tests. This would signify that changing the reinforcement fiber would markedly effect material performance.

The change in flexural fracture load, when comparing the test materials, was not this dramatic. As with all the tests performed for this study, the addition of any reinforcement fiber resulted in a decrease in the flexural strength of the test specimen. The reasons advanced for this decrease in performance during the impact and tensile tests are also valid for the flexural test. The impact of fiber orientation, microstructural coring, and extrusion process variability can all be cited as possible explanations of this decrease in material performance.

Analysis of the material performance test data of the two fibers under study indicated a slight (11%) performance advantage for the oatstraw reinforced test specimens. The mean experimental fracture load of the oatstraw specimens was 6623 newtons (see Figure 20). Soybean stalk reinforcement specimens performed only slightly worse with a mean experimental fracture load of 5849 newtons.

Statistical analysis of the test data collected for the flexural tests indicated that variance due to different fiber types had a $\underline{p}$ value reading of 0.2145 and a $\underline{F}$ ratio value of 1.934. This would indicate that different fiber types was a factor in the mean experimental flexural fracture load values but was not a substantial one. $\underline{F}$ ratio values of around 1 indicate that variation was attributable to random error. With a $\underline{F}$ ratio value of 1.934, fracture load variation can be attributed to the effect of different fiber types.

The Effect of Fiber Length

Test data on the effects of different fiber lengths on flexural strength was, like the data on fiber types, lacking any clear and dramatic evidence that this variable was of significance. Moreover, the mean experimental test values for the three fiber lengths (0.64, 1.19, and 3.81 centimeters) were all very similar in magnitude. The use of

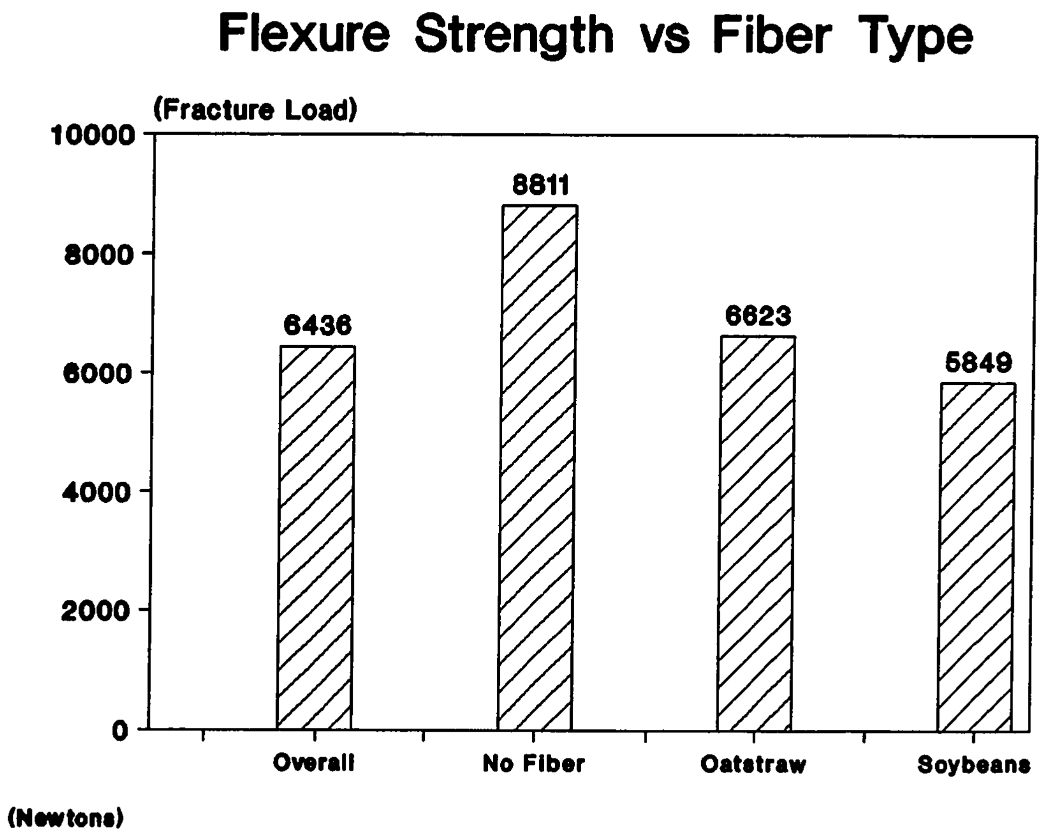


Figure 20. Flexure strength vs fiber type.

reinforcement fibers did, as with all the tests, result in a decrease of flexural fracture load when compared to the sample with no fiber reinforcement. The mean fracture loads of the three fiber lengths tested were all within 5% of each other (see Figure 21).

The test data collected during the flexure tests indicated that test specimens with no fiber reinforcement material had the highest fracture loads (8811 newtons). The

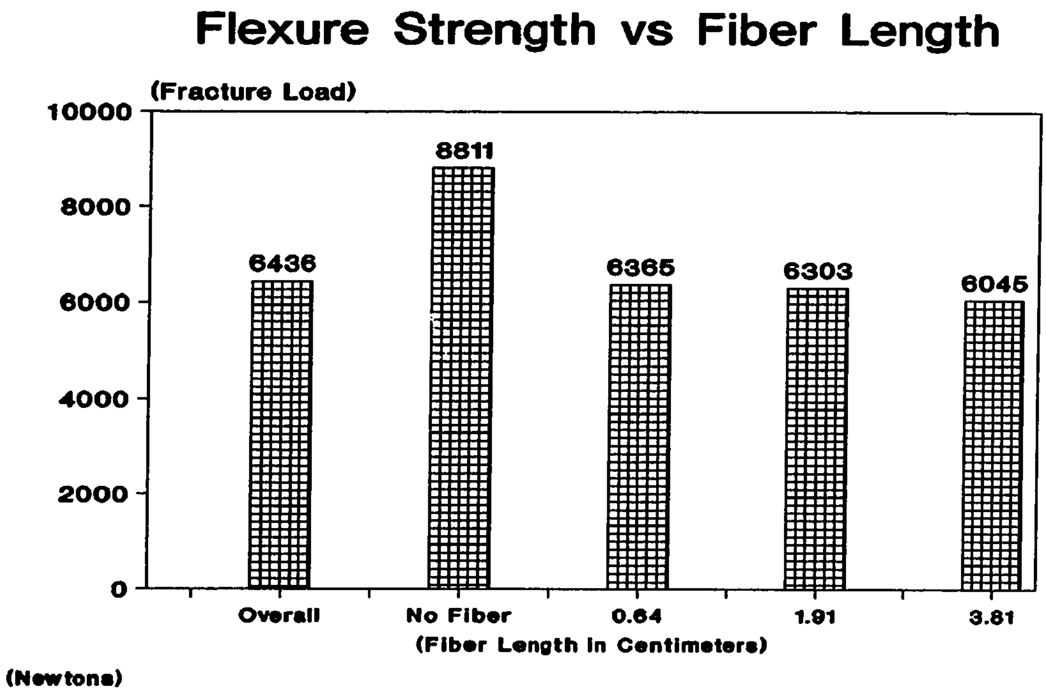


Figure 21. Flexure strength vs fiber length.

performance of the other fiber lengths were very similar to each other. Reinforcement fiber with a length of 0.64 centimeters had a fracture load of 6365 newtons. Samples with a fiber length of 1.91 centimeters fractured under a mean load of 6303 newtons. Specimens with the longest fiber length (3.81 centimeters) broke with a mean fracture load of 6045 newtons.

Statistical analysis of the data complied during the tests indicated that different fiber length treatments had a *p* value of 0.4797 and a *F* ratio reading of 0.919. This would support the contention that differential fiber reinforcement lengths were not responsible for the variations in the flexural fracture loads of the test specimens and was not a significant treatment effect. These variations were attributable to random error.

The Effect of Fiber Volume Fraction Percentage

Analysis of the importance of the impact of variable fiber percentages on flexural fracture strength indicated that this variable was not significant. As with all the flexural tests, there was no dramatic indication of the significance or insignificance of this variable.

Unfortunately, flexural strength decreased 27% in the test specimens with the use of reinforcement fiber. An analysis of the test data collected (see Figure 22) indicated that the mean experimental fracture strength for 25% fiber reinforced samples was 6418 newtons. Test specimens with approximately 30% fiber reinforcement fractured at 6058 newtons.

Statistical analysis of the test data collected indicates that the variable fiber volume fraction percentage treatment had a p value reading of 0.7514 and a F ratio value of 0.307. These statistical values suggest that variable fiber reinforcement percentages are not a significant factor in explaining the variations in flexural fracture strength values.

Analysis of the statistical data presented in Table 24, located in Appendix E, indicated that only variable that

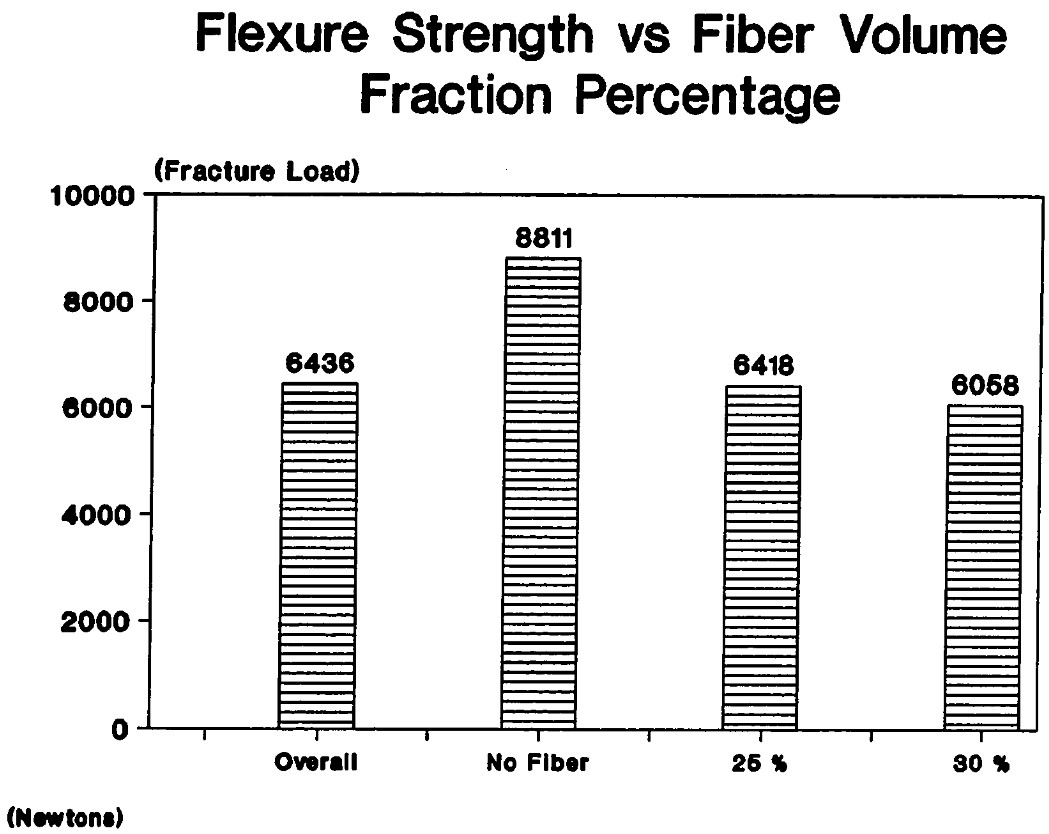


Figure 22. Flexure strength vs fiber volume fraction percentage.

was of significance was fiber type. All other treatment effects, either individual or combined, were not significant.

Summary

The collected numerical test data from the 336 impact, tensile, and flexure tests were analyzed using single and multiple ANOVA tests for independent means at a confidence level of 95% (0.05 level of significance) to determine if significant mean value differences existed between the treatment groups. Rank-order tables were constructed based upon the mean impact values, mean fracture load values, mean test specimen elongation values, and mean flexure fracture load values. Graphs of these dependent variables were constructed and analyzed in this chapter. Tables of the test data were constructed and located in appropriate appendices.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The contents of this chapter are presented under the following headings: (a) Summary of the Study, (b) Conclusions, and (c) Recommendations.

Summary of the Study

The problem in this study was to generate engineering data on a new composite material under development at the University of Northern Iowa. The engineering data generated was to provide a clearer understanding of the effect of different types of reinforcement materials, varied percentages of fiber reinforcement material (fiber volume fraction), different lengths of fiber reinforcement material, and the treatment effect of different operating temperatures. This improved understanding of the effects of these variables was to be used in predicting the structural performance of this new composite material.

The tests performed on this composite material were all standard engineering tests prescribed by the American Society for Testing and Materials. No special manufacturing or testing procedures were used.

The data collected from these tests were presented and statistically analyzed under the following headings: (a) Impact Tests, (b) Tensile Tests, and (c) Flexure Tests. Single and multiple treatment effects were analyzed using a Analysis of Variance (ANOVA) tests.

The following hypotheses were made in regard to this study: (H_1) Comparisons between the types of fiber reinforcement material used will show a significant difference in the mean impact values as measured by ASTM D 256-90b and (H_{01}) that there will be no significant difference between the mean impact values in regard to different types of fiber reinforcement. (H_2) Comparisons between different percentages of fiber reinforcement material used will show a significant difference in the mean impact values as measured by ASTM D 256-90b and (H_{02}) that there will be no significant difference between the mean impact values in regard to different percentages of fiber reinforcement. (H_3) Comparisons between different treatment temperatures used will show a significant difference in the mean impact values as measured by ASTM D 256-90b and (H_{03}) that there will be no significant difference between the mean impact values in regard to different treatment temperatures.

(H_4) Comparisons between the types of fiber reinforcement material used will show a significant difference in the mean tensile strength values as measured by ASTM D 638-90 and (H_{04}) that there will be no significant difference between the mean tensile strength values in regard to different types of fiber reinforcement. (H_5) Comparisons between different percentages of fiber reinforcement material used will show a significant difference in the mean tensile strength values as measured by ASTM D 638-90 and (H_{05}) that there will be no significant difference between the mean tensile strength values in regard to different percentages of fiber reinforcement. (H_6) Comparisons between different treatment temperatures used will show a significant difference in the mean tensile strength values as measured by ASTM D 639-90 and (H_{06}) that there will be no significant difference between the mean tensile strength values in regard to different treatment temperatures.

(H_7) Comparisons between the lengths of fiber reinforcement material will show a significant difference in the mean tensile strength values as measured by ASTM D 638-90 and (H_{07}) that there will be no significant difference between the mean tensile strength values in regard to different treatment fiber lengths.

Conclusions

Data were collected and presented in tabular and graphical format for 193 notch impact tests, 130 tensile tests and 13 flexure tests. In consideration of that presentation and in regard to the subsequent data analyses and subject to the stated assumptions and limitations of this study, the following conclusions are presented:

1. Visual examination of the microstructure of the prototype composite lumber revealed that distinctive coring of the material occurred. This microstructural coring

indicates that a higher extrusion pressure was needed to manufacture this composite. As a result of this manufacturing variable, the mechanical properties of the test specimens showed significant differences based on the amount of coring contained in the sample. All test samples had decreased notch impact, tensile, and flexural mechanical properties when agricultural fiber reinforcement material was used. The effect of extrusion operating variables (i.e. compression ratio, temperature, pressure, and friction) and the subsequent microstructure coring prevented the fiber reinforcement material in the inner core layer from properly absorbing the load applied after the matrix began plastic deformation. Instead, the fibers acted as point sources for crack initiation. This property resulted in a drop in mechanical properties when compared to a control material.

2. Statistical analysis of the test data revealed that p value and critical F ratio readings existed for all the treatment effects. These readings were used in determining the significance of the treatment effects as expressed in the hypotheses.

3. In regard to null hypothesis H_{01}, that comparisons between the types of fiber reinforcement material would show no significant difference, at the 0.05 level, in the mean impact values as measured by ASTM D 256-90b, the null hypothesis is strongly rejected due to a critical F ratio value of 26.915 and a p value reading of 0.0000. Because

different types of fiber reinforcement material was shown to be a significant influence on mean impact values, hypothesis H_1 is accepted.

4. In regard to null hypothesis H_{02}, that comparisons between the percentages of fiber reinforcement material would show no significant difference, at the 0.05 level, in the mean impact values as measured by ASTM D 256-90b, the null hypothesis is strongly rejected due to a critical $\underline{F}$ ratio value of 26.995 and a $\underline{p}$ value reading of 0.0000. Because different percentages of fiber reinforcement material was shown to be a significant influence on mean impact values, hypothesis H_2 is accepted.

5. In regard to null hypothesis H_{03}, that comparisons between the temperatures of the test specimens would show no significant difference, at the 0.05 level, in the mean impact values as measured by ASTM D 256-90b, the null hypothesis is accepted due to a critical $\underline{F}$ ratio value of 1.361 and a $\underline{p}$ value reading of 0.2591. Because different temperatures of test specimens was not shown to be a significant influence on mean impact values, hypothesis H_3 is rejected.

6. In regard to null hypothesis H_{04}, that comparisons between types of fiber reinforcement material would show no significant difference, at the 0.05 level, in the mean tensile strength as measured by ASTM D 639-90, two measures of criteria were mentioned (Fracture Load and Elongation).

The tests were conducted using two test groups with a 90^0 orientation shift. The first group of test samples (Group 1) was manufactured with a vertical cross section orientation. The second batch of test specimens (Group 2) had a horizontal orientation to the sample cross section. The statistical analysis of this data indicated that those test groups reacted differently. In regard to the statistical data concerning fracture load, the null hypothesis (H_{04}) is rejected due to a critical $\underline{F}$ ratio values of 11.917 (Group 1) and 10.489 (Group 2) and $\underline{p}$ value readings of 0.0000 for Group 1 and 0.0007 for Group 2. Because different types of fiber reinforcement materials were shown to be a significant influence on mean tensile strength, hypothesis H_4 (Fracture Load) is accepted. In regard to Elongation, the null hypothesis H_{04} (Elongation) can not be accepted or rejected because the two test groups provided contradictory information. For test Group 1, null hypothesis H_{04} can be rejected because of a critical $\underline{F}$ ratio value of 12.005 and a $\underline{p}$ value reading of 0.0000. However, in regard to the Group 2 tensile tests, null hypothesis H_{04} (that there is no significance to different fiber types) is accepted due to a critical $\underline{F}$ ratio value of 1.049 and a $\underline{p}$ value reading of 0.0000. The orientation change in the test specimens and the microstructural coring problems of the test samples has revealed an inconsistency in the material characteristics of the composite material under study.

Because of the inconclusive data, in regard to hypothesis H_4 (Elongation), the author can not accept or reject the null hypothesis in relation to the effect of different fiber reinforcement materials on the elongation. Further manufacturing and testing of this hypothesis is recommended.

7. In regard to null hypothesis H_{05}, that comparisons between percentages of fiber reinforcement material will show no significant differences, at the 0.05 level, in the mean tensile strength as measured by ASTM D 639-90, two measures of criteria was mentioned (Fracture Load and Elongation). The tests were conducted using two test groups with a 90^0 orientation shift. The statistical analysis of this data indicated that those test groups reacted differently. In regard to the statistical data concerning fracture load, the null hypothesis can not be accepted or rejected due to a critical $\underline{F}$ ratio values of 8.107 (Group 1-vertical orientation) and 1.152 (Group 2-horizontal orientation) and $\underline{p}$ value readings of 0.0005 for Group 1 and 0.3425 for Group 2. The statistical analysis indicates that each sample group had unique material and mechanical properties. The null hypothesis can not be accepted or rejected, in regard to elongation also, due to a critical $\underline{F}$ ratio values of 11.243 (Group 1) and 0.296 (Group 2) and $\underline{p}$ value readings of 0.0000 (Group 1) and 0.7478 (Group 2). Because different percentages of fiber reinforcement materials could not be shown to be a significant or

insignificant influence, on the mean tensile strength, hypothesis H_5 can not be accepted or rejected. The author believes that the reasons discussed for difficulties with conclusion 6 also apply to this conclusion. Further manufacturing and testing of this hypothesis is recommended.

8. In regard to null hypothesis H_{06}, that comparisons between the lengths of fiber reinforcement will show no significant differences, at the 0.05 level, in the mean impact values as measured by ASTM D 256-90b, the null hypothesis is strongly rejected due to a critical $\underline{F}$ ratio value of 16.364 and a $\underline{p}$ value reading of 0.0000. Because different lengths of fiber reinforcement was shown to be a significant influence on mean impact values, hypothesis H_6 is accepted.

9. In regard to null hypothesis H_{07}, that comparisons between lengths of fiber reinforcement material will show no significant differences, at the 0.05 level, in the mean tensile strengths as measured by ASTM D 638-90, two measures of criteria was mentioned (Fracture Load and Elongation). The tests were conducted using two test groups with a 90^0 orientation shift. The statistical analysis of this data indicated that those test groups reacted differently. In regard to the statistical data concerning fracture load, the null hypothesis can be rejected due to a critical $\underline{F}$ ratio values of 3.072 (Group 1) and 6.807 (Group 2) and $\underline{p}$ value readings of 0.0311 for Group 1 and 0.0024 for Group 2. The

statistical analysis indicates that while each sample group had unique material and mechanical properties, the overall effect of different fiber lengths on mean tensile strength (Fracture Load) was significant. However, the null hypothesis can not be accepted or rejected, in regard to elongation, due to a critical F ratio values of 13.381 (Group 1) and 1.171 (Group 2) and p value readings of 0.0000 (Group 1) and 0.7478 (Group 2). Because different lengths of fiber reinforcement materials could not be shown to be a significant or insignificant influence, on the mean tensile strength, hypothesis H_7 can not be accepted or rejected. The author believes that the reasons discussed for difficulties with conclusion 6 and 7 also apply to this conclusion. Further testing of this hypothesis is recommended.

10. In regard to the flexure tests, only different fiber types had a significant impact on the flexural fracture loads required to break the specimens. Statistical analysis indicated that different fiber types treatment had a critical F ratio value of 1.934 and a p value reading of 0.2145. All other treatment effects (fiber length or fiber volume fraction percentage) or combinations of treatment effects were not significant.

Recommendations

The following recommendations are based on the literature review, conclusions of this study, and the statistical data analyses.

1. Further cooperation in applied research is crucial to both academia, researchers, and the commercial plastics industry and should be encouraged.

2. Similar study should be conducted with different types of fiber reinforcement materials, fiber lengths, and fiber volume fractions in order to support the conclusions of this study.

3. Similar study should be made with the materials studied in this research but should concentrate on different extruded form sizes, shapes, and extrusion operating variables.

4. Study should be done of the effect of the environment on the properties of this material.

5. Study of the use of these materials as a substitute for lumber in the construction field.

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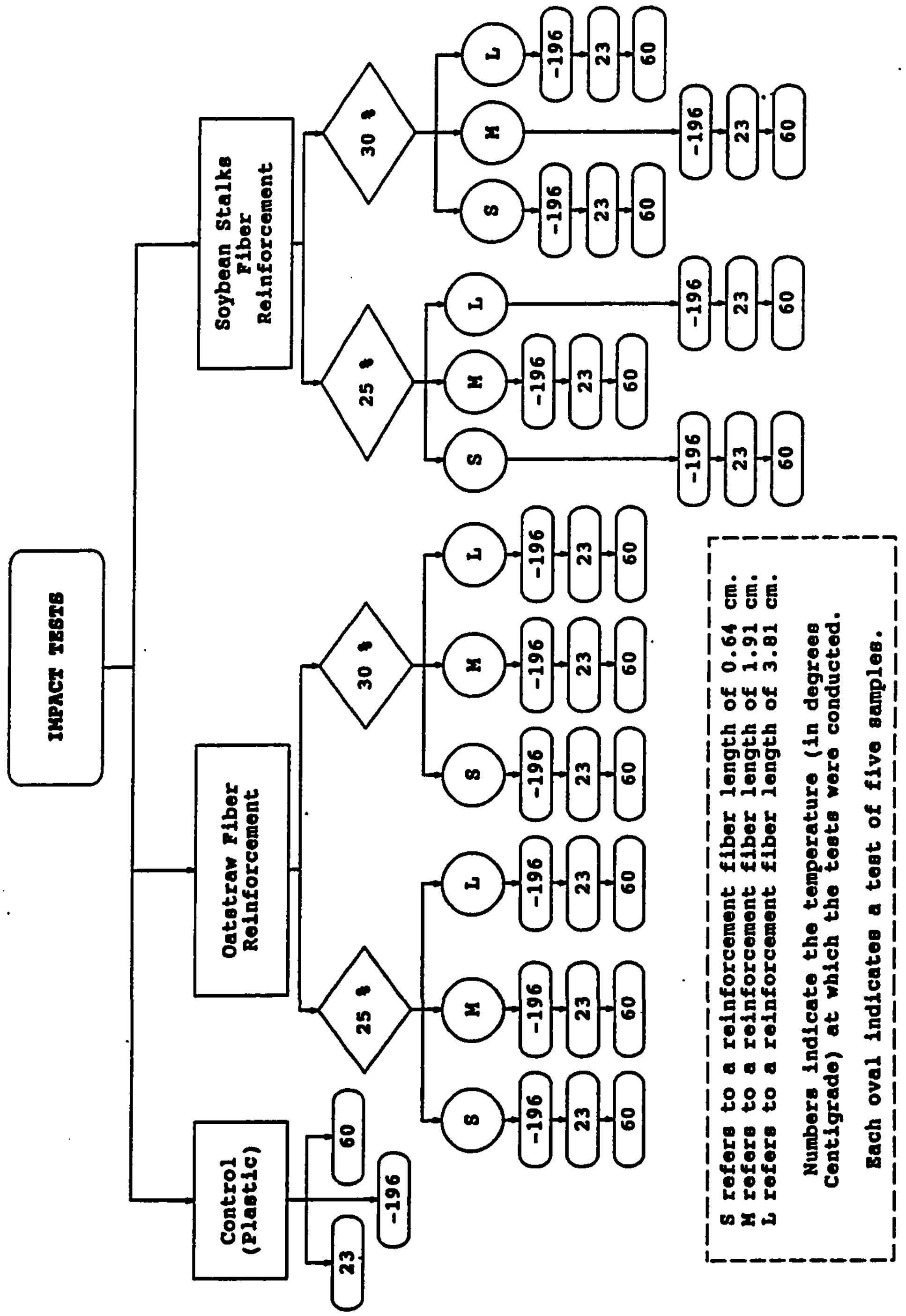
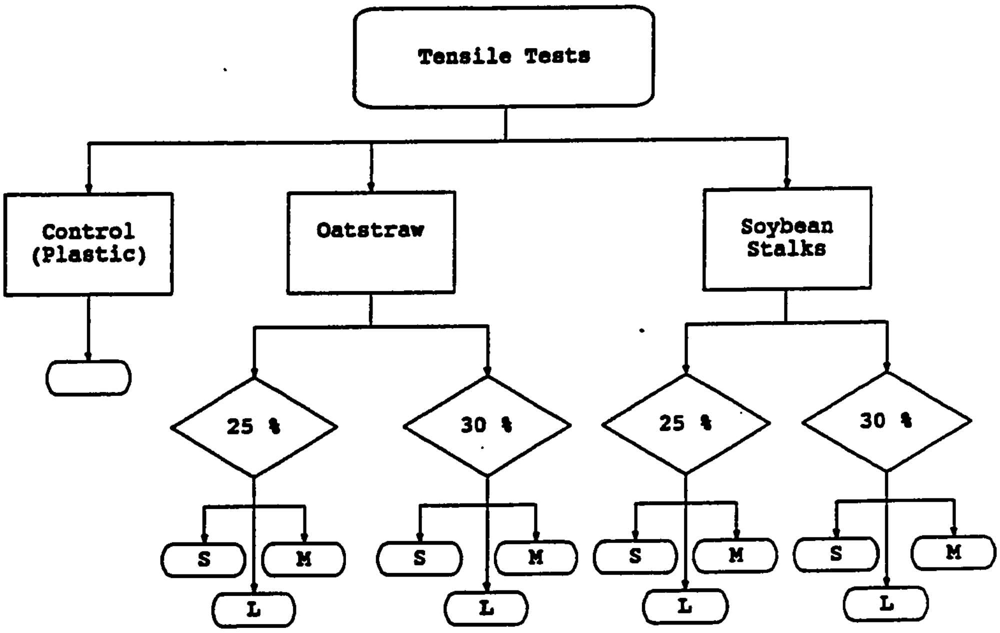
APPENDIX A

EXPERIMENTAL DESIGN FLOW CHARTS


IMPACT TESTS
Control (Plastic)
60
-196
23
Oatstraw Fiber Reinforcement
Soybean Stalks Fiber Reinforcement
25 %
30 %
S
M
L
-196
23
60
S refers to a reinforcement fiber length of 0.64 cm.
M refers to a reinforcement fiber length of 1.91 cm.
L refers to a reinforcement fiber length of 3.81 cm.
Numbers indicate the temperature (in degrees Centigrade) at which the tests were conducted.
Each oval indicates a test of five samples.

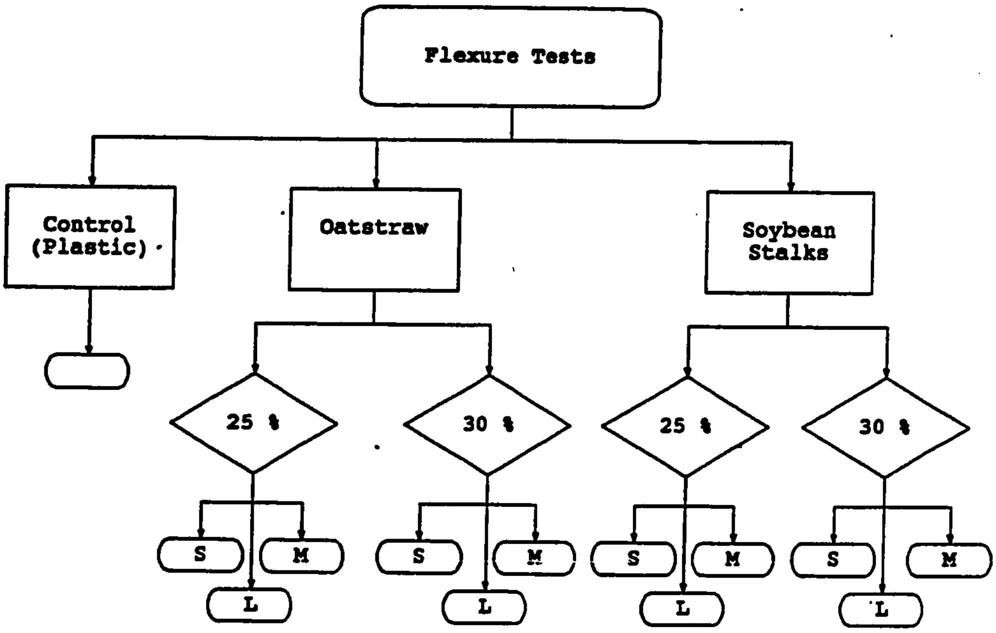


S refers to a reinforcement fiber length of 0.64 cm.

M refers to a reinforcement fiber length of 1.91 cm.

L refers to a reinforcement fiber length of 3.81 cm.

Each oval indicates a minimum test of five samples.



S refers to a reinforcement fiber length of 0.64 cm.

M refers to a reinforcement fiber length of 1.91 cm.

L refers to a reinforcement fiber length of 3.81 cm.

APPENDIX B

IMPACT TEST ANOVA TABLES

Table 2

Mean Experimental Values For Notched Impact Tests

Overall and Individual Variables

Treatment	T	F	L	P	n	M	SD
Overall					193	7.33	4.24
T	23				65	9.88	3.32
	60				65	8.79	3.61
	- 196				63	3.20	2.12
F		C			15	10.81	6.20
		S			90	7.72	4.36
		O			88	6.34	3.33
L			0.00		15	10.81	6.20
			0.64		59	7.24	3.67
			1.91		60	7.01	3.99
			3.81		59	6.87	4.15
P				0	15	10.81	6.20
				25	88	7.29	4.04
				30	90	6.79	3.80

Note. Dependent variable is maximum fracture load measured in joules per second, fiber length is in centimeters, and temperatures are celsius. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 3

Mean Experimental Values For Notched Impact Tests

Sums of Squares Based On Unique Variance

Treatment	*df*	SS(U)	MSS	*F*	*p*
T	2	1147612	573806	1.361	0.2591
F	2	136421575	68210787	26.915	0.0000
L	3	124409484	41469828	16.364	0.0000
P	2	136824727	68412363	26.995	0.0000
TF	4	13703166	3425791	8.125	0.0000
TL	6	11106117	1851019	4.390	0.0004
TP	4	15000518	3750129	8.895	0.0000
FL	6	277107261	46184543	18.224	0.0000
FP	4	344859969	86214992	34.020	0.0000
LP	6	265975706	44329284	17.492	0.0000
TFL	12	36147560	3012296	6.973	0.0000
TFP	8	31986793	3998349	9.256	0.0000
TLP	12	26564184	2213682	5.125	0.0000
FLP	12	220472941	18372745	7.250	0.0000
TFLP	24	176	7	0.724	0.8227

Note. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 4

Mean Experimental Values For Notched Impact Tests

Temperature (T), Fiber Type (F), Fiber Length (L) and Fiber Volume Fraction Percentage (P)

Treatment	T	F	L	P	*n*	*M*	*SD*
TF	23	C			5	15.87	1.50
	60	C			5	13.78	2.86
	23	S			30	10.25	2.92
	60	S			30	9.54	3.53
	23	O			30	8.51	2.70
	60	O			30	7.21	2.78
	- 196	S			30	3.38	2.66
	- 196	O			28	3.10	1.60
	- 196	C			5	2.77	0.65
TL	23		0.00		5	15.87	1.50
	60		0.00		5	13.78	2.86
	23		0.64		20	9.77	1.95
	23		1.91		20	9.47	2.89
	23		3.81		20	8.90	3.74
	60		1.91		20	8.78	3.17
	60		0.64		20	8.40	3.45
	60		3.81		20	7.94	3.58
	- 196		3.81		19	3.60	3.14
	- 196		0.64		19	3.37	1.54
	- 196		1.91		20	2.78	1.61
	- 196		0.00		5	2.77	0.65
TP	23			0	5	15.87	1.50
	60			0	5	13.78	2.86
	23			25	30	9.47	2.83
	23			30	30	9.29	3.06
	60			25	30	8.93	3.81
	60			30	30	7.82	2.81
	- 196			30	30	3.28	2.63
	- 196			25	30	3.14	1.70
	- 196			0	5	2.77	0.65

Note. Dependent variable is maximum fracture load measured in joules per second, fiber length is in centimeters and temperatures are celsius.

Table 5

Mean Experimental Values For Notched Impact Tests Fiber Type (F), Fiber Length (L) and Fiber Volume Fraction Percentage (P)

Treatment	T	F	L	P	n	M	SD
FL		C	0.00		15	10.81	6.20
		S	3.81		30	8.87	4.50
		S	0.64		30	7.32	4.16
		O	0.64		29	7.17	3.16
		O	1.91		30	7.04	3.79
		S	1.91		30	6.97	4.25
		O	3.81		29	4.79	2.42
FP		C		0	15	10.81	6.20
		S		30	45	7.85	4.25
		S		25	45	7.59	4.46
		O		25	43	6.98	3.58
		O		30	45	5.74	2.98
LP			0.00	0	15	10.81	6.20
			1.91	25	30	8.01	4.26
			0.64	25	29	7.92	4.02
			3.81	30	30	7.79	4.49
			0.64	30	30	6.59	3.22
			1.91	30	30	6.01	3.49
			3.81	25	29	5.92	3.59

Note. Dependent variable is maximum fracture load measured in joules per second and fiber length is in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 6

Mean Experimental Values For Notched Impact Tests

Temperature (T), Fiber Type (F), and Fiber Length (L)

Treatment	T	F	L	P	n	M	SD
TFL	23	C	0.00		5	15.87	1.50
	60	C	0.00		5	13.78	2.86
	23	S	3.81		10	11.23	3.66
	60	S	3.81		10	10.89	1.97
	23	S	0.64		10	9.81	1.99
	23	O	0.64		10	9.72	2.01
	23	S	1.91		10	9.71	2.92
	23	O	1.91		10	9.23	2.99
	60	S	1.91		10	8.99	3.32
	60	S	0.64		10	8.74	4.72
	60	O	1.91		10	8.56	3.17
	60	O	0.64		10	8.07	1.61
	23	O	3.81		10	6.58	2.04
	60	O	3.81		10	5.00	1.98
	- 196	S	3.81		10	4.50	4.02
	- 196	S	0.64		10	3.50	1.78
	- 196	O	1.91		10	3.34	2.02
	- 196	O	0.64		10	3.33	1.32
	- 196	C	0.00		5	2.77	0.65
	- 196	O	3.81		9	2.59	1.37
	- 196	S	1.91		10	2.22	1.79

Note. Dependent variable is maximum fracture load measured in joules per second, fiber length is in centimeters, and temperatures are celsius. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 7

Mean Experimental Values For Notched Impact Tests Temperature (T), Fiber Type (F), and Fiber Volume Fraction Percentage (P)

Treatment	T	F	L	P	n	M	SD
TFP	23	C		0	5	15.87	1.50
	60	C		0	5	13.78	2.86
	23	S		30	30	10.68	3.29
	60	S		25	15	10.29	3.94
	23	S		25	15	9.82	2.54
	23	O		25	15	9.13	3.15
	60	S		30	15	8.79	3.02
	23	O		30	15	7.91	2.09
	60	O		25	15	7.57	3.23
	60	O		30	15	6.85	2.29
	- 196	S		30	15	4.09	3.49
	- 196	O		25	13	3.82	2.01
	- 196	C		0	5	2.77	0.65
	- 196	S		25	15	2.66	1.19
	- 196	O		30	15	2.47	0.75

Note. Dependent variable is maximum fracture load measured in joules per second and temperatures are celsius. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 8

Mean Experimental Values For Notched Impact Tests Temperature (T), Fiber Length (L), and Fiber Volume Fraction Percentage (P)

Treatment	T F	L	P	n	M	SD
TLP	23	0.00	0	5	15.87	1.50
	60	0.00	0	5	13.78	2.86
	23	1.91	25	10	10.92	2.92
	23	3.81	30	10	10.34	4.18
	23	0.64	25	10	10.04	1.63
	60	1.91	25	10	9.84	2.76
	60	0.64	25	10	9.63	4.43
	75	0.64	30	10	9.50	2.28
	60	3.81	30	10	8.58	3.35
	23	1.91	30	10	8.02	2.10
	23	3.81	25	10	7.47	2.75
	60	3.81	25	10	7.31	3.87
	60	0.64	30	10	7.17	1.46
	- 196	3.81	30	10	4.44	3.99
	- 196	0.64	25	10	3.68	1.43
	- 196	1.91	25	10	3.27	2.04
	- 196	0.64	30	10	3.09	1.65
	- 196	0.00	0	5	2.77	0.65
	- 196	3.81	25	9	2.65	1.55
	- 196	1.91	30	10	2.30	0.89

Note. Dependent variable is maximum fracture load measured in joules per second, fiber length is in centimeters, and temperatures are celsius. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 9

Mean Experimental Values For Notched Impact Tests

Fiber Type (F), Fiber Length (L), and Fiber Volume Fraction Percentage (P)

Treatment	T F	L	P	n	M	SD
FLP	C	0.00	0	15	10.81	6.20
	S	3.81	25	15	10.17	4.72
	O	1.91	25	15	8.56	3.85
	O	0.64	25	14	8.12	2.92
	S	0.64	25	15	7.75	4.94
	S	3.81	25	15	7.58	4.01
	S	1.91	25	15	7.46	4.70
	S	0.64	30	15	6.89	3.31
	S	1.91	30	15	6.49	3.85
	O	0.64	30	15	6.28	3.21
	O	1.91	30	15	5.53	3.15
	O	3.81	30	15	5.40	2.69
	O	3.81	25	14	4.14	1.98

Note. Dependent variable is maximum fracture load measured in joules per second and fiber length is in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 10

Mean Experimental Values For Notched Impact Tests

Temperature (T), Fiber Type (F), Fiber Length (L), and Fiber Volume Fraction Percentage (P)

Treatment	T	F	L	P	n	M	SD
TFLP	23	C	0.00	0	5	15.87	1.50
	60	C	0.00	0	5	13.78	2.86
	23	S	3.81	30	5	12.83	4.66
	23	O	1.91	25	5	11.33	1.54
	60	S	3.81	30	5	11.19	2.12
	60	S	0.64	25	5	10.77	6.20
	23	O	0.64	25	5	10.77	1.21
	60	S	3.81	25	5	10.59	2.00
	23	S	1.91	25	5	10.50	4.05
	23	S	0.64	30	5	10.29	2.26
	60	O	1.91	25	5	10.17	2.45
	23	S	3.81	25	5	9.63	1.45
	60	S	1.91	25	5	9.52	3.30
	23	S	0.64	25	5	9.34	1.80
	23	S	1.91	30	5	8.92	1.11
	23	O	0.64	30	5	8.71	2.25
	60	O	0.64	25	5	8.50	1.61
	60	S	1.91	30	5	8.47	3.64
	23	O	3.81	30	5	7.84	1.44
	60	O	0.64	30	5	7.64	1.66
	23	O	1.91	30	5	7.13	2.58
	60	O	1.91	30	5	6.95	3.18
	60	S	0.64	30	5	6.71	1.22
	- 196	S	3.81	30	5	6.50	4.99
	60	O	3.81	30	5	5.97	1.92
	23	O	3.81	25	5	5.31	1.81
	- 196	O	0.64	25	5	4.36	1.00
	- 196	O	1.91	25	5	4.18	2.59
	60	O	3.81	25	5	4.03	1.67
	- 196	S	0.64	30	5	3.37	2.10
	- 196	S	0.64	25	5	3.13	1.59
	- 196	O	3.81	25	4	2.83	2.09
	- 196	C	0.00	0	5	2.77	0.65
	- 196	S	3.81	25	5	2.51	1.20
	- 196	O	0.64	30	5	2.51	0.92
	- 196	O	1.91	30	5	2.51	0.85
	- 196	O	3.81	30	5	2.39	0.62
	- 196	S	1.91	25	5	2.37	0.74

APPENDIX C

TENSILE TEST ANOVA TABLES

GROUP 1

Table 11

Mean Experimental Values For Tensile Tests Overall and Individual Variables (Fracture Load and Elongation)

Treatment	F	L	P	n	M	SD
		Fracture Load (newtons)				
Overall				106	269.84	114.76
F	C			6	396.59	60.71
	S			50	301.94	123.14
	O			50	222.52	85.90
L		0.00		6	396.59	60.71
		1.91		33	277.71	125.85
		0.64		33	257.66	96.13
		3.81		34	251.65	116.44
P			0	6	396.59	60.71
			25	47	293.36	126.81
			30	53	234.64	91.65
		Elongation (cm)				
Overall				106	0.64	0.13
F	C			6	0.86	0.23
	S			33	0.65	0.09
	O			33	0.61	0.13
L		0.00		6	0.86	0.23
		0.64		33	0.66	0.09
		1.91		33	0.66	0.12
		3.81		34	0.56	0.10
P			0	6	0.86	0.23
			25	47	0.64	0.13
			30	53	0.62	0.10

Table 12

Mean Experimental Values For Tensile Tests (Fracture Load and Elongation) Sums of Squares Based On Unique Variance

Treatment	df	SS(U)	MSS	F	p
		Fracture Load			
F	2	13133	6566	11.917	0.0000
L	3	5790	1930	3.072	0.0311
P	2	9505	4752	8.107	0.0005
FL	6	2473942473	412323745	4.106	0.0010
FP	4	4016483090	1004120772	9.999	0.0000
LP	6	12783	2130	3.694	0.0024
FLP	12	22555	1879	3.693	0.0001
		Elongation			
F	2	0.05296	0.02648	12.005	0.0000
L	3	0.07911	0.02637	13.381	0.0000
P	2	0.05020	0.02510	11.243	0.0000
FL	6	54683	9113	4.047	0.0012
FP	4	51349	12837	5.701	0.0004
LP	6	0.08445	0.01407	7.121	0.0000
FLP	12	0.12778	0.01065	6.501	0.0000

Note. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 13

Mean Experimental Values For Tensile Test Fracture Load (Fiber Type (F), Fiber Length (L) and Fiber Volume Fraction Percentage (P))

Treatment	F	L	P	n	M	SD
FL	C	0.00		6	396.69	60.72
	S	1.91		16	320.98	153.86
	S	0.64		16	299.72	100.04
	S	3.81		18	287.00	115.79
	O	1.91		17	236.96	76.46
	O	0.64		17	218.10	75.26
	O	3.81		16	211.91	106.98
FP	C		0	6	396.69	60.72
	S		25	25	339.53	136.56
	S		30	25	264.31	96.79
	O		25	25	240.87	92.12
	O		30	25	208.04	79.40
LP		0.00	0	6	396.69	60.72
		3.81	25	17	312.27	131.36
		1.91	25	14	294.74	157.64
		0.64	25	16	272.45	91.99
		1.91	30	19	265.16	100.10
		0.64	30	17	244.07	100.71
		3.81	30	17	191.05	53.82

Note. Dependent variable is maximum fracture load measured in newtons and fiber length is in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 14

Mean Experimental Values For Tensile Tests

Fracture Load (Fiber Type (F), Fiber Length (L), and Fiber Volume Fraction Percentage (P))

Treatment	F	L	P	n	M	SD
FLP	C	0.00	0	6	396.60	60.72
	S	1.91	25	7	375.56	174.99
	S	3.81	25	9	347.90	134.96
	S	0.64	25	9	303.15	109.74
	S	0.64	30	7	295.27	94.44
	S	1.91	30	9	278.55	129.58
	O	3.81	25	8	272.14	123.08
	O	1.91	30	10	253.10	66.06
	O	0.64	25	7	232.11	42.26
	S	3.81	30	9	226.06	43.68
	O	1.91	25	7	213.91	89.36
	O	0.64	30	10	208.27	92.88
	O	3.81	30	8	151.68	33.01

Note. Dependent variable is maximum fracture load measured in newtons and fiber length is in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 15

Mean Experimental Values For Tensile Test Elongation (Fiber Type (F), Fiber Length (L), and Fiber Volume Fraction Percentage (P))

Treatment	F	L	P	n	M	SD
FL	C	0.00		6	1.01	0.23
	O	1.91		17	0.69	0.13
	S	0.64		16	0.67	0.09
	O	0.64		17	0.65	0.08
	S	3.81		18	0.64	0.07
	S	1.91		16	0.62	0.10
	O	3.81		16	0.48	0.05
FP	C		0	6	1.01	0.23
	S		25	25	0.66	0.10
	S		30	25	0.63	0.07
	O		25	22	0.62	0.15
	O		30	28	0.60	0.11
LP		0.00	0	6	1.01	0.23
		0.64	25	16	0.69	0.10
		1.91	25	14	0.67	0.13
		1.91	30	19	0.65	0.11
		0.64	30	17	0.63	0.06
		3.81	30	17	0.56	0.09
		3.81	25	17	0.56	0.11

Note. Dependent variable is test sample elongation measured in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 16

Mean Experimental Values For Tensile Tests

Elongation (Fiber Type (F), Fiber Length (L), and Fiber Volume Fraction Percentage (P))

Treatment	F	L	P	n	M	SD
FLP	C	0.00	0	6	1.01	0.23
	O	1.91	25	7	0.73	0.12
	S	0.64	25	9	0.71	0.10
	O	0.64	25	7	0.68	0.10
	O	1.91	30	10	0.66	0.13
	S	3.81	25	9	0.65	0.08
	O	0.64	30	10	0.64	0.05
	S	3.81	30	9	0.63	0.07
	S	0.64	30	7	0.63	0.07
	S	1.91	30	9	0.63	0.09
	S	1.91	25	7	0.61	0.11
	O	3.81	30	8	0.49	0.04
	O	3.81	25	8	0.47	0.06

Note. Dependent variable is test sample elongation measured in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

APPENDIX D

TENSILE TEST ANOVA TABLES

GROUP 2

Table 17

Mean Experimental Values For Tensile Tests Overall and Individual Variables (Fracture Load and Elongation)

Treatment	F	L	P	n	M	SD
				Fracture Load (newtons)		
Overall				24	580.94	166.32
F	C			2	881.19	166.32
	S			11	627.91	65.71
	O			11	479.39	163.99
L		0.00		2	881.19	166.32
		3.81		7	655.98	84.85
		0.64		8	537.57	147.57
		1.91		7	469.69	137.23
P			0	2	881.19	166.32
			30	11	566.53	167.50
			25	11	540.73	122.11
				Elongation (cm)		
Overall				24	0.87	0.17
F	C			2	1.00	0.02
	O			11	0.88	0.21
	S			11	0.83	0.12
L		0.00		2	1.00	0.02
		1.91		7	0.90	0.23
		0.64		8	0.87	0.12
		3.81		7	0.79	0.14
P			0	2	1.00	0.02
			25	11	0.91	0.20
			30	11	0.80	0.11

Table 18

Mean Experimental Values For Tensile Tests (Fracture Load and Elongation) Sums of Squares Based On Unique Variance

Treatment	df	SS(U)	MSS	F	p
		Fracture Load			
F	2	16069	8034	10.489	0.0007
L	3	16245	5415	6.807	0.0024
P	2	34895192	17447596	1.152	0.3425
FL	6	163938463	27323077	0.572	0.7458
FP	4	36474230	91186807	1.910	0.1687
LP	6	7856745	13094574	0.864	0.5425
FLP	12	28362	2360	6.781	0.0017
		Elongation			
F	2	0.00881	0.00440	1.049	0.3681
L	3	0.01449	0.00483	1.171	0.3457
P	2	79.59	39.79	0.296	0.7478
FL	6	1171	195	0.348	0.8985
FP	4	1203	300	0.537	0.7114
LP	6	1155	192	1.434	0.2658
FLP	12	0.07248	0.00604	2.712	0.0545

Note. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 19

Mean Experimental Values For Tensile Test Fracture Load (Fiber Type (F), Fiber Length (L), and Fiber Volume Fraction Percentage (P))

Treatment	F	L	P	*n*	*M*	*SD*
FL	C	0.00		2	881.19	78.64
	O	3.81		3	679.24	120.50
	S	0.64		4	660.78	36.39
	S	3.81		4	638.54	61.43
	S	1.91		3	569.82	80.65
	O	0.64		4	414.35	94.93
	O	1.91		4	394.56	125.62
FP	C		0	2	881.19	78.64
	S		30	5	641.79	85.01
	S		25	6	616.30	50.00
	O		30	6	503.85	199.90
	O		25	5	450.07	123.75
LP		0.00	0	2	881.19	78.64
		3.81	30	4	705.04	74.42
		3.81	25	3	590.59	45.42
		0.64	25	4	565.72	90.92
		0.64	30	4	509.45	201.10
		1.91	25	4	478.41	177.66
		1.91	30	3	458.03	93.77

Note. Dependent variable is maximum fracture load measured in newtons and fiber length is in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 20

Mean Experimental Values For Tensile Tests Fracture Load (Fiber Type (F), Fiber Length (L), and Fiber Volume Fraction Percentage (P))

Treatment	F	L	P	n	M	SD
FLP	C	0.00	0	2	881.19	78.64
	O	3.81	30	2	745.74	50.00
	S	0.64	30	2	680.58	48.44
	S	3.81	30	2	665.01	86.52
	S	0.64	25	2	640.99	6.94
	S	3.81	25	2	612.74	31.45
	S	1.91	25	2	595.17	95.64
	O	3.81	25	1	546.24	0.00
	S	1.91	30	1	519.11	0.00
	O	0.64	25	2	490.42	45.59
	O	1.91	30	2	427.47	109.47
	O	1.91	25	2	361.64	176.15
	O	0.64	30	2	338.29	42.48

Note. Dependent variable is maximum fracture load measured in newtons and fiber length is in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 21

Mean Experimental Values For Tensile Test Elongation (Fiber Type (F), Fiber Length (L), and Fiber Volume Fraction Percentage (P))

Treatment	F	L	P	n	M	SD
FL	C	0.00		2	1.00	0.02
	O	1.91		4	0.97	0.30
	O	0.64		4	0.91	0.10
	S	0.64		4	0.84	0.15
	S	3.81		4	0.83	0.16
	S	1.91		3	0.82	0.05
	O	3.81		3	0.73	0.11
FP	C		0	2	1.00	0.02
	O		25	5	0.96	0.27
	S		25	6	0.87	0.11
	O		30	6	0.81	0.11
	S		30	5	0.77	0.12
LP		0.00	0	2	1.00	0.02
		1.91	25	4	1.00	0.26
		0.64	30	4	0.88	0.13
		0.64	25	4	0.87	0.13
		3.81	25	3	0.85	0.21
		1.91	30	3	0.76	0.09
		3.81	30	4	0.74	0.07

Note. Dependent variable is test sample elongation measured in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 22

Mean Experimental Values For Tensile Tests Elongation (Fiber Type (F), Fiber Length (L), and Fiber Volume Fraction Percentage (P))

Treatment	F	L	P	n	M	SD
FLP	O	1.91	25	2	1.19	0.22
	C	0.00	0	2	1.00	0.02
	S	3.81	25	2	0.97	0.00
	O	0.64	30	2	0.91	0.11
	O	0.64	25	2	0.90	0.12
	S	0.64	25	2	0.84	0.18
	S	0.64	30	2	0.84	0.18
	S	1.91	25	2	0.81	0.07
	S	1.91	30	1	0.81	0.00
	O	3.81	30	2	0.79	0.04
	O	1.91	30	2	0.74	0.11
	S	3.81	30	2	0.69	0.04
	O	3.81	25	1	0.61	0.00

Note. Dependent variable is test sample elongation measured in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

APPENDIX E

FLEXURE TEST ANOVA TABLES

Table 23

Mean Experimental Values For Flexure Tests Overall and Individual Variables (Fracture Load)

Treatment	F	L	P	n	M	SD
				Fracture Load		
Overall				23	6436.58	912.78
F	C			1	8811.93	0.00
	O			6	6623.40	544.02
	S			6	5849.41	347.85
L		0.00		1	8811.93	0.00
		0.64		4	6365.41	563.59
		3.81		4	6303.13	930.12
		1.91		4	6045.13	191.72
P			0	1	8811.13	0.00
			25	6	6418.78	683.69
			30	6	6058.48	480.85

Note. Dependent variable is maximum fracture load measured in newtons and fiber length is in centimeters. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.

Table 24

Mean Experimental Values For Flexure Tests (Fracture Load)

Sums of Squares Based On Unique Variance

Treatment	df	SS(U)	MSS	F	p
		Fracture Load			
F	2	2218823703	1109411851	1.934	0.2145
L	3	1580899597	526966532	0.919	0.4797
P	2	1074941690	537470845	0.307	0.7514
FL	6	4352414375	725402395	0.415	0.8393
FP	4	2742812184	685703046	0.228	0.9022
LP	6	3072379506	512063251	0.170	0.9615
FLP	12	505165	42097	*	*

Note. * indicates values have collapsed over this factor. Letters used in this table indicate the following treatment effects: T represents temperature, F indicates fiber types (C is control, S is soybeans, and O is oatstraw), L is fiber length in cm, and P is volume fraction percentage.